ENVIRONMENTAL SUSTAINABILITY AND ENGINEERING PERFORMANCE OF OPC-FLY ASH MORTAR MIXES WITH DIFFERENT WORKABILITY

PUTRI ZULAIHA BINTI RAZI

FACULTY OF ENGINEERING

UNIVERSITY OF MALAYA

2014

ENVIRONMENTAL SUSTAINABILITY AND ENGINEERING PERFORMANCE OF OPC-FLY ASH MORTAR MIXES WITH DIFFERENT WORKABILITY

PUTRI ZULAIHA BINTI RAZI

DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER ENGINEERING SCIENCE

FACULTY OF ENGINEERING

UNIVERSITY OF MALAYA

2014

UNIVERSITI MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: **Putri Zulaiha Binti Razi**

Registration/Matric No: **KGA 110003**

Name of Degree: **Master Engineering Science**

Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"):

Environmental Sustainability and Engineering Performance of OPC-Fly Ash Mortar Mixes with Different Workability

Field of Study: **Structural Engineering and Materials**

I do solemnly and sincerely declare that:
(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date 23 October 2014

Subscribed and solemnly declared before,

Witness's Signature Date 23 October 2014

Name:

Designation:

ABSTRACT

Engineering performance and environmental sustainability of mortar mixes through the incorporation of different replacement levels of fly ash at 10%, 20%, 40% and 60% respectively were investigated. Samples of mortar were prepared by using four different water / binder ratios of 0.35, 0.40, 0.45 and 0.50, and were also prepared with different dosages of superplasticizer to give three ranges of workability that is normal, high and self-compacting spread flow. Engineering performance was assessed through compressive strength at 3, 7, 14, 28 and 90 days and the durability aspect through the water absorption test when mortar reached 28 days of age. Environmental performance or basically the sustainability aspect was assessed through the determination of CO_2 footprint which denotes the environmental impact of each mix. The relationship that is to be investigated lies in the potential of CO_2 reduction in the mortar mixes, when cement was replaced by fly ash. Analysis of relative performance index for engineering performances and environmental sustainability found that regardless of the w/b ratios, for every type of flow, 60% replacement of fly ash gave the lowest relative performance index with an average of 50% less than OPC mortar. Cost analysis revealed that, cost per kg of mortar for self-compacting flow increased by 44% compared to normal flow. Optimum mix analysis found that with replacement of 10% to 20% of fly ash, gave a balance in environmental sustainability performance and engineering performance

ABSTRAK

Tahap prestasi kejuruteraan dan kemampanan alam sekitar bagi campuran simen mortar melalui penggantian abu terbang yang mempunyai peratusan berbeza 10%, 20%, 40% dan 60% masing-masingbdikaji. Sampel mortar disediakan dengan menggunakan 2empat air / pengikat nisbah yang berbeza 0.35 , 0.40 , 0.45 dan 0.50, dan juga disediakan dengan dos bahan tambah yang berbeza untuk memberi tiga julat kebolehkerjaan iaitu normal , tinggi dan simen mortar terpadat sendiri . Prestasi Kejuruteraan telah dinilai melalui kekuatan mampatan pada 3, 7, 14 , 28 dan 90 hari dan aspek ketahanan melalui ujian penyerapan air apabila mortar mencapai usia 28 hari. Prestasi alam sekitar atau pada dasarnya aspek kemampanan telah dinilai melalui penentuan tahap CO_2 sebagai tanda aras kesan alam sekitar bagi setiap campuran. Hubungan terhadap potensi pengurangan tahap CO_2 dalam mortar campuran adalah aspek yang dilihat, apabila kandungan simen digantikan dengan abu terbang. Analisis terhadap indeks prestasi relatif bagi prestasi kejuruteraan dan kemampanan alam sekitar menunjukkan tanpa mengira nisbah air/pengikat, untuk setiap jenis campuran 60% abu terbang menunjukkan tahap indeks prestasi yang rendah dengan purata 50% daripada simen mortar biasa. Analisis kos pula mendapati kos bagi setiap kg mortar terpadat sendiri adalah lebih tinggi sebanyak 44% jika dibandingkan dengan aliran normal. Analisis bagi menentukan campuran optimum mendapati bahawa penggantian abu terbang sebanyak 10% ke 20% memberikan penggantian yang paling optimum kerana dapat membantu dalam kesimbangan kemampanan alam sekitar dan juga pretasi kejuruteraan.

ACKNOWLEDGEMENT

The author would like to express her utmost gratitude to her supervisor, Professor Dr. Hashim Bin Abdul Razak for his invaluable advice, guidance and patience throughout the duration of this study. Numerous people have contributed towards the success of this research. The author wishes to thank the following individuals namely En. Mansor, En. Khairul, En. Ayob (Concrete Laboratory) for their dedicated and unfailing technical support. The author is indebted to his research colleague En. Teuku Ferdi, Mr. Jegathish, who have rendered assistance throughout the course of this study. Last but not least, the author would like to express her deepest appreciation to her beloved husband, En. Arif Azlee Bin Zainudin and beloved families for their endless love, support and encouragement.

DEDICATION

To my other half

Arif Azlee Bin Zainudin

and my little angel

Putri Nurqaseh Adelia Binti Arif Azlee

TABLE OF CONTENT

CHAPTER 2	LITERATURE REVIEW	PAGE

CHAPTER 3	RESEARCH METHODOLOGY	PAGE

CHAPTER 4 RESULTS AND DISCUSSION PAGE

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 4.33	Cost-strength for w/b 0.50	118
Figure 4.34	Cost-CO_2 footprint w/b 0.35	120
Figure 4.35	Cost-CO_2 footprint w/b 0.40	121
Figure 4.36	Cost-CO_2 footprint w/b 0.45	122
Figure 4.37	Cost-CO_2 footprint w/b 0.50	123
Figure 4.38	Optimum replacement mix based to compressive strength w/b 0.35	126
Figure 4.39	Optimum replacement mix based to compressive strength w/b 0.40	127
Figure 4.40	Optimum replacement mix based to compressive strength w/b 0.45	128
Figure 4.41	Optimum replacement mix based to compressive strength w/b 0.50	129
Figure 4.42	Optimum replacement mix based to water absorption w/b 0.35	131
Figure 4.43	Optimum replacement mix based to water absorption w/b 0.40	132
Figure 4.44	Optimum replacement mix based to water absorption w/b 0.45	133
Figure 4.45	Optimum replacement mix based to water absorption w/b 0.50	134

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

CO_2	Carbon dioxide
GHG	Green house gases
SCC	Self-compacting concrete
SCM	Self-compacting mortar
SP	Superplasticizer
FA	Fly ash
μm	Micrometer
GGBFS	Ground granulated blast furnace slag
OPC	Ordinary Portland cement
MPa	Mega Pascal
N_2O	Nitrous Oxide
CH_4	Methane
PFC	Perfluorocarbons
HFC	Hydrofluorocarbons
SF_6	Sulphur hexafluoride
GWP	Global warming potential
CO_2-e	Carbon Dioxide Equivalent
SAP	Standard Assessment Procedure
WBCSD	World Business Council for Sustainable Development

LIST OF SYMBOLS AND ABBREVIATIONS

CKD	Cement kiln dust
$CaCO_3$	Calcium carbonate (Limestone)
SiO_4	Quartz
$CaSO_4$	Calcium sulphate (Gypsum)
NaCl	Sodium chloride
K_2SO_4	Arcanite
$2(C_2S)\cdot CaCO_3$	Spurite
$2(C_2S)\cdot CaSO_4$	Sulphospurite
CaO	Calcium oxide (Lime)
$Ca\ (OH)_2$	Calcium hydroxide (Free Lime)
H_2O	Hydroxide
TNT	trinitrotoluene
ANFO	Ammonium nitrate and fuel oil
AA	Alkali-activated
XRF	X-ray fluorescence

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.0 Introduction

Sustainability has become a central issue in the construction industry nowadays. Sustainable construction implementation and the effort to create green buildings has become a significant subject in Malaysia in current years and have been addressed under the Malaysian Construction Industry Master Plan (2005 – 2015). As a productive sector, the construction industry constantly contributes significantly to the Malaysian economy. Current statistics depicts that construction industries growth recorded 5.3% in 2007 and this value put in 2.1% of the total Gross Domestic Product (GDP) of Malaysia (Kamar & Hamid, 2011). These have led to the enforcement of law by the Ministry Of Energy, Green Technology and Water for the construction players in meeting sustainable requirements for their construction projects. These include the utilization of green materials, the provision of safe environment, and the utilization of non-toxic or non-hazardous materials during pre- and post- construction activities. Based to the Kyoto Protocol 1997, The United Nations Climate Change conference in Bali 2007, G8 Summit in Italy 2009, and Copenhagen Commitment 2009, with the objective to assist in combating the climate change many developed countries targeting for realistic greenhouse gas (GHG) emission reduction (Ng, Chen, & Wong, 2013). Signed in 1997, the Kyoto protocol aim for decreasing the greenhouse gas emissions in developed countries by 5.2% from the 1990 level by 2008–2012. With respect to Kyoto protocol goals, in order to reduce its CO_2 emissions, cement industry has been optimistic maintaining and developing its manufacturing process. The European Union commenced the Emissions Trading Directive in 2003, in order to practise the Kyoto target, plant-specific CO_2 caps establish into the major power manufacturing and energy intensive industry sectors (e.g. cement, oil refining, steel, pulp, and paper) (Europian Union, 2003). Significant cost impact will occur if the cement industries fail in meeting the quotas, hence they are strongly encouraged to follow the protocol.

Cement plays a vital task in terms of financial and public significance since its principal rests in building and improving infrastructure facilities. Concrete and mortars, a cement based material are utilize in particularly bulk quantity. World population growth and the urban development in many countries will definitely warrant the utilization of cement and cement-based materials. For instance, concrete production was recorded for more than 10 billion tons back in 2009. It is also crucial to note that this industry also generates heavy pollutants. A total of 4% global warming origins from human activities were released from cement production which accounted for 5-6%. These leads to release large amounts of organic pollutants, including dioxins and heavy metals also particles (Rodrigues & Joekes, 2010). It was reported that without any changes in technology and scientific method, 50% CO_2 will simply released by the production of cement industry (Lund, 2007).

Sustainability is mainly governed by three main pillars namely economy, social and environmental. Economy is a contributor to sustainability, where the utilization of any green material will help provide low economic impact and in addition will boost Malaysia's gross profit. Through the utilization of waste materials, this will somehow help mitigate the hazard to the community and improve the social life of the community itself since safer environment is able to be created. The environment is the main factor contributing to sustainable issues, since we are nowadays troubled by the ozone depletion which is harmful to our atmosphere. Large amount of greenhouse gases released may cause the depletion of ozone. The clinker production in cement manufacturing is established for quite some time as a main contributor of CO_2 emission worldwide. Attempts to reduce CO_2 emission in concrete include reducing the clinker content in the cement production since one tonne of carbon dioxide (CO_2) tends to be produced during the production of one tonne clinker (Fantilli & Chiaia, 2013); this means that the CO_2 emission in concrete mixes is reduced by minimizing the cement content. In order to do this, a constituent material or supplementary cementing materials or preferably fly ash is required to replace and reduce the cement content. CO_2 which is emitted during the production of concrete can be measured by examining the CO_2 footprint of the concrete.

Fly ash is products that originate from the ignition of pulverized coal from thermal power plants. The system so called as powder-collection eliminates the fly ash, as a fine particulate residue, from the combustion gases before they are released into the atmosphere. Fly ash which is categorized as a fine waste material is the most consumed mineral additive added to concrete mix production worldwide. (Malhotra and Ramezanianpour, 1994) maintain that inclusion of fly ash in concrete, may affects most aspects of concrete since it acts both as fine aggregate or a cementitious component. Fly ash affects the rheological properties in fresh state and strength, porosity and durability during the hardened state. In spite of that, it helps in saving the cost and energy consumed in the manufacturing of concrete.

In Malaysia, fly ash is categorized as an industrial waste material, where it is normally deposited into landfill. Fly ash is normally discarded to the environment without giving any financial return; normally there is merely environmental pollution observed, together with issues of disposal (Karim, Zain, Jamil, Lai, & Islam, 2011). Billion tons of industrial wastes are generated annually and the amount of land-filled wastes are radically increased in consequence of industrial development and urbanization (Zhang, Gao, Gao, Wei, & Yu, 2013). For instance, production of fly ash in Malaysia is believed approaching over 2 million tons annually and anticipated to double-up in 2013 since the stipulation for energy is increased fast (RockTron

International, 2010). The increased production of fly-ash from thermal plants causes the quantities of fly-ash deposited into landfills to double. Thus, less consumption in the industrial waste materials will result in the disposal landfill space being occupied by time. Furthermore, the occupied space in landfills nowadays has become environmental problems worldwide. This issues become even worse since it is reported by (Izquierdo & Querol, 2012) that leachate of fly ash deposited into the landfill produces traceable elements that may harm the environment and consequently leading to the social community being exposed to hazard .

Mortar has been extensively used as binder and in rectification of structural works. Conventional-type mortar using the combination of sand, cement and water has been used since decades. As mortar serves as the basis for the workability properties of self-compacting concrete (scc), these properties could be assessed by self-compacting mortars (scm) which serve .As an integral part of designing self-compacting concrete, self-compacting mortar acts as basis for the workability properties (Şahmaran, Christianto, & Yaman, 2006).

Engineering properties is the common measure for determining the characteristics and nature of any materials. Engineering properties can be categorized into two states which are the fresh state behaviour and hardened state behaviour. Fresh state is determined as the materials are in raw condition or mixed in dry or wet condition. Fresh state measurement in mortar mixes includes the slump flow, V-funnel, density, viscosity. Meanwhile, the hardened state is determined as the mixes undergo a hardening process and in a hardened physical state, normally in cube or cylindrical cube. The measurements for the hardened state include the compressive strength, absorption test, shrinkage test and other measurements.

1.1 Background of Problems

High sensitivity to greenhouse issues, global warming and sustainability at present times has become major concern in this research. Environmental issues have become central to economic and political debates these days. Since the cement manufacturing generates the largest percentage of the production of carbon dioxide in the environment and approximately 5% of the world's anthropogenic CO_2 emissions, the use of cement in concrete technology should be minimized. Portland cement is accountable for 74% to 81% of the total CO_2 emission and leading as primary source of CO_2 emission released by concrete producers (Flower & Sanjayan, 2007). Typical approaches to alleviate emissions, solely on the production of cement, will not be capable to compensate the increase by factor of 2.5 for the next 40 years of cement-based products. Further improvements are necessary including raise in the effectiveness of cement use (Damineli, Kemeid, Aguiar, & John, 2010). Using residues from other industrial sectors can also improve the sustainability of cement industry (F. A. Rodrigues, 2011). A major decrease of Portland cement clinker in the concrete will occur by utilizing superplasticizer sufficiently and usage of high reactive cements. Furthermore, optimization of particle-size distribution and lessening the water proportion will provides similar reduction of cement clinker (Proske, Hainer, Rezvani, & Graubner, 2013).

In order to minimize the usage of ordinary Portland cement in concrete technology, waste products such as fly ash powder are used that acts as a substitution of cement in concrete. Sustainable technology is also seen as a key element in serving to diminish greenhouse issue. Environmental sustainability in concrete mixtures was mainly focused on producing "green concrete" by using or replacing part of the mixture with "green products". Recent research that has focused particularly on the environmental sustainability aspect in concrete is done by (Henry, Pardo, Nishimura, & Kato, 2011).

(Becchio, Corgnati, Kindinis, & Pagliolico, 2009) replacing ordinary aggregates with wastes from woodworking activities known as mineralized wood concrete (MWC) as an opportunity for composing additional sustainable lightweight concrete

(Fantilli & Chiaia, 2013) in their research investigate the combination of mechanical behaviour and the environmental aspect. They were targeting of develop an ecological concrete with satisfactory engineering performances, by proposing an index of ecological-mechanical ratios.

Concrete is material that commonly used widely as building material in the world. Producing green concrete is the aim of this research and to implement it, mortar was selected as the main subject. The utilization of waste material is synonymous with the production of green concrete, since waste materials such as fly ash that is deposited into landfills without further consumption, consume a lot more space in landfill than necessary and it will further become environmental problems worldwide. Conventional concrete has become too common when replaced with waste materials, thus new technology in concrete so-called the self-compacting concrete (scc) initially developed in Japan has been adopted in this research. With the aim to produce green concrete by utilizing fly ash, and produce less CO_2 to the environment, environmental sustainability becomes a key criterion in ensuring that the green issues are achieved. Thus, CO_2 footprint is determined and a relationship between environmental sustainability and engineering performances is developed.

1.2 Research Objectives

i. To determine the effect of fly ash for different flowability mortar.

ii. The relationship between engineering properties performance (strength and durability) and environmental sustainability performance (CO_2 footprint)

iii. To produce an index of environmental sustainability performance against engineering properties performance of self-compacting mortar.

iv. To generate the relationship between the cost factor over engineering properties and environmental sustainability.

1.3 Research Scope

The scope of this research covers:

i. The effect of superplasticizer dosage for the flowability of normal slump flow, high slump flow and self-compacting flow mortar.

ii. The relationship between engineering properties (strength and durability) and environmental sustainability performance (CO_2 footprint)

iii. The index of environmental sustainability performance against engineering properties performance.

iv. The relationship between cost factor over engineering properties and environmental sustainability.

1.4 Research Significance

This research will hopefully assist other researchers in the field of concrete in giving attention to the engineering performance as well as to the sustainability of the environment. The work on combating the global warming issues will enhance better awareness of cement and concrete producers particularly in terms of the usage of green materials for sustainability development.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter presents a review on existing research that is relevant to the current study, with the objective of providing sufficient background information to facilitate the understanding and evaluation of this research. The chapter begins with awareness that the dramatic increase of the utilization of self-compacting concrete (SCC) in the construction industry. Simultaneously, previous researches particularly in self-compacting mortar were reviewed. The addition of mineral additives fly ash in concrete and mortar was discussed pertaining to its abilities enhancing the engineering properties performance. Sustainability issues were reviewed to the major discussed topic i.e environmental and economical. Approached in measuring CO_2 footprint was also highlighted, and the methods involved in measuring the CO_2 emission were also addressed.

2.1 Past Work on SCM

Self-compacting technology was first developed in Japan in the late 1980s specifically for high-rise buildings (Ozawa, Maekawa, Okamura, 1990). SCC comprises of social, economical and environmental sustainable technology. Due to the radical development that takes place in concrete technology, SCC is believed to act correspondingly to the most current industrial needs (Figueiras, Nunes, Coutinho, & Figueiras, 2009) . Over the decades, this technology has attracted many researchers which are evident in the published studies concerning SCC. SCC has an aptitude to flow under its own weight and may consolidate itself without any means of compaction (Benabed, Kadri, Azzouz, & Kenai, 2012; Dehwah, 2012; Uysal & Yilmaz, 2011).

Concrete placement without the means of vibration is a challenge to the construction industry. In order to achieve such behaviour, it is a necessity that fresh concrete has to maintain both high fluidity and good cohesiveness at the same time (Corinaldesi & Moriconi, 2011).

Mortars with different binder types have been used since ancient times for different purposes (Elsen, 2006). SCM is synonymous with SCC, and is preferred due to its easiness during mixing yet provides excellent flowing ability during the fresh state (Safiuddin, West, & Soudki, 2011). The SCM philosophy is similar to that of the SCC whereby the mortar mix will flow by itself without having any means of compacting it. This philosophy may reduce the overall casting expenditure and a more homogeneous product will be produced. Previous research particularly focused on self-compacting mortar had been conducted by (Felekoğlu, Tosun, Baradan, Altun, & Uyulgan, 2006; Felekoğlu, Türkel, & Altuntaş, 2007; Guo, Ling, & Poon, 2012; Libre, Khoshnazar, & Shekarchi, 2010; Rizwan & Bier, 2012; Safiuddin et al., 2011; Şahmaran, Christianto, & Yaman, 2006; Uygunoğlu & Topçu, 2010). SCM is favoured for healing and repairing concrete structures, particularly for the congested cast area. In structural repairs, the repair material should at least give the satisfactory engineering performance or improved mechanical properties (Poston, 2001). There is a potential to develop good engineering performance of mortars by using additive sources from chemical, mineral, polymer and fibre. Shrinkage and permeability of mortar will be reduce while producing SCM with addition of chemical admixture, also using mineral additives such as fly ash and ground granulated slag could increase the strength.

In order to get the 'self-compacting' ability, the addition of chemical admixture is essential in order to improve the workability and diminish segregation (Khatib, 2008). Superplasticizer (SP) or water reducer agent is required to enhance the flowing ability. The incorporation of SP will help in controlling the shear stress (Nepomuceno, Oliveira,

& Lopes, 2012). The excessive superplasticizer in the mortar mix will cause segregation in the form of bleeding. In order to avoid such problem, an appropriate constituent of fine materials called the minerals admixtures such as fly ash, ground granulated blast slag, rice husk ash, silica fume, and palm oil fuel ash may be add in towards giving better separation resistance, and sustaining the fluid capability for fresh SCM.

The utilization of fine mineral admixtures in SCMs is foreseeable improve the self-compactability quality and to decrease material expenditure of self-compacting concrete (SCC), (Turk, 2012). Most of the constituent fine materials mentioned are waste materials which are the by-product from various industrial sectors and are abundantly available in Malaysia. The incorporation of these fine materials in SCC has successfully been proven in improving the engineering properties of SCC. Among the constituent materials mentioned, fly ash (FA) is the common constituent materials used in self-compacting concrete or mortar.

2.2 Fly Ash as Mineral Additives

Fly ash has been employ in concrete for decades. The utilization has more extensive since huge quantity of the material are now accessible, i.e. after the clean air regulations forced power plants to install scrubbers and electrostatic precipitators to entrap the fine particles which earlier went up the smokestacks and are release into the environment further causing hazard to health and the environment (Meyer, 2009). Recent research incorporating fly ash as mineral admixtures particularly in SCC was carried out by (Bentz, Hansen, & Guynn, 2011; Dehwah, 2012; Gesoğlu, Güneyisi, Kocabağ, Bayram, & Mermerdaş, 2012; N.Bouzoubaa,Lachemi, 2001; Sabet, Libre, & Shekarchi, 2013; Siddique, 2011). According to (Malhotra and Ramezanianpour, 1994), fly-ash is a by-product of the combustion of pulverized coal in thermal power plants. They come in the form of spherical particles with diameter ranging from < 1 μm up to

150 µm. Fly ashes also demonstrate pozzolanic activity, which is described in ASTM C618-93. As a siliceous and aluminous material, pozzolan is having less cementitous value. However, if it is finely divided, with present of moisture, it might respond with lime (tolerated by hydrating Portland cement) at normal temperature to produce mixes which own cementitous properties. By using fly ash as mineral admixture, it is believed to be more suitable compared to other types of material for quality control of SCC (Barbhuiya, 2011).

The most important advantages of fly ash that it is a by-product of coal ignition and as a schedule waste product that has to be disposed frequently and requires high cost. However, concrete with addition of fly ash shows enhancement in strength and good toughness properties compared to the normal concrete. The sources of fly ash from coal burning are also widely available. Additionally, Portland cement is commonly costlier material compared to fly ash. However, the disadvantage of fly ash utilization is that it gave comparatively low in early strength enhancement. It has been a practise to indicate 90 day strengths instead of 28 day strengths particularly for mass concrete structures such as dams and heavy foundations since they are design for years after casting. Concrete enhancer is always the best choice to enhance hydration rates of fly ash concrete mixes if conventional strength development is crucial. Factor of differences in coal sources particularly from one power plant to others may creates variation in the physical and chemical criteria of fly ash. As the result of shortened combustion processes also large amount loss of ignition may cause to intolerable carbon levels emission. Variation of chemical composition and quality control create more serious problem and challenges. However, by developing scientific technologies, the fly ash producers has managed to provide better quality control in order to efficiently split the unburned material (Meyer, 2009).

The composition of the inert portion reflecting the class of fly ashes which are categorized into two classes, F and C. Class F fly ashes are originated from bituminous and sub-bituminous coals and contain vigorous mechanism of aluminosilicate glasses, whereas class C fly ashes contains high levels of calcium oxide, comprised in the glassy fraction which are develop from the lignitic coals and contain calcium aluminosilicate glasses (Mindess, Young & Darwin, 2003). Since fly ash is less expensive compared to Portland cement, thus their usage can be considered economically worth. Furthermore, the addition of fly ash in concrete mixture is seen to give many technical values and advantages. Many Class C fly ashes, with present of water will hydrate and set within 45 minutes. Replacement of 15% to 25% by weight of cement often used for class F fly ash while replacement of 15% to 40% often selected for class C fly (Halstead, 1986). Replacement of fly ash differs with the reactivity of the ash and the required performance on the concrete (Mindess et al., 2003). In fact, workability and long-term strengths are achieved while fly ash is added in concretes mixture that caused by their spherical morphology. Apparent reason is that, they perform as small balls to diminish the inter-particle friction. In combating the heat of hydration, permeability, and bleeding fly ash is the best option for concrete mixture. By providing better sulphate resistance, controlling alkali-silica reaction, decreasing chloride diffusion, resulting to better durability of concrete. Apparent reason for that is utilization of fly ash may reduce leachate process by reacting with calcium hydroxide (which is the most soluble of the hydration products) and improve the pore structure. Due to the effect of residual carbon from the ash, it gave disadvantages such as reducing air-entraining capability and early strength development (Gebler and Klieger, 1986).

In order to achieve the targeted flowability, SCC need an additional admixture such as fly ash, superplasticizer and other industrial waste compounds such as iron slag waste from steel mill wastes in the form of fine aggregate (Raharjo & Subakti, 2013). (Lange et. Al, 1997) conclude the addition of specific replacement of fly ash may lessen the water proportion thus provides better workability. Particle of fly ash that are spherical shape caused it to easily roll of each other's and diminish the interparticle friction, thus will improve the workability properties (Ramachandran, 1995). It is well understood that consumption of fly ash (FA) in concrete will improve workability and enhancing towards the long-term strength development. The utilization of fly ash assists in the workability by increasing the slump of the concrete mixture without increasing its cost, furthermore by incorporating fly ash it will also eliminate the need for viscosity-enhancing chemical admixtures. Also, due to the decrease in heat of hydration, thermally induced cracking will be diminish thus gave a better rheological properties of concrete. By using lower water content, good durability and better mechanical reliability will be achieved (Dinakar, Babu, & Santhanam, 2008). Since fly ash helps in increasing the durability properties of concrete, therefore it will also help extend the life-time service of the concrete structures.

The rate of strength development rate for concrete when substitute with fly ash is found to be lower at the initial stage compared to concrete that contains only plain Portland cement. However, as illustrated in Figure 2.1, concrete with fly ash does continue to gain strength, which explains that after a period of time, the strength of concrete will be higher than that containing ordinary Portland cement. The pozzolanic activity develops the strength of the transition zone, i.e. the interface between the paste and aggregate, in the concrete by secondary effects. Furthermore, better packing of particles in the fresh state when fly ash is included will reduce the porosity, hence also leading to higher strength (Illston, 2001). In addition, by using high volume of fly ash, high strength, low shrinkage with high absorption will be achieved (Khatib, 2008). Fly ash (FA) and ground granulated blast furnace slag (GGBFS) extensively increase the workability and compressive strength of SCC mixtures that by replacing 25% of ordinary Portland Cement (OPC) with fly ash will result in a strength of more than 105 MPa at 400 days (Uysal & Sumer, 2011).

By looking into the environmental value aspect, fly ash is found to assist in lowering the environmental impact. It is reported that by utilizing fly ash in concrete mixes, it is able in decreasing the CO_2 emissions by 13% to 15% in normal concrete mixes (Flower & Sanjayan, 2007). (Björk, 1999) reported that each tonne of cement that is replaced by fly ash will help in reducing the CO_2 emissions in concrete by approximately one tonne. Efficient utilization of industrial wastes such as fly ash as supplementary cementitious materials provide significant role in CO_2 emissions reduction, resources and energy conservation of the cement industry (Zhang et al., 2013). Investigation on the greenhouse emissions of concrete and cement, also the impact of fly ash replacement on total emissions has extensively been studied (Flower & Sanjayan, 2007; Henry et al., 2011).

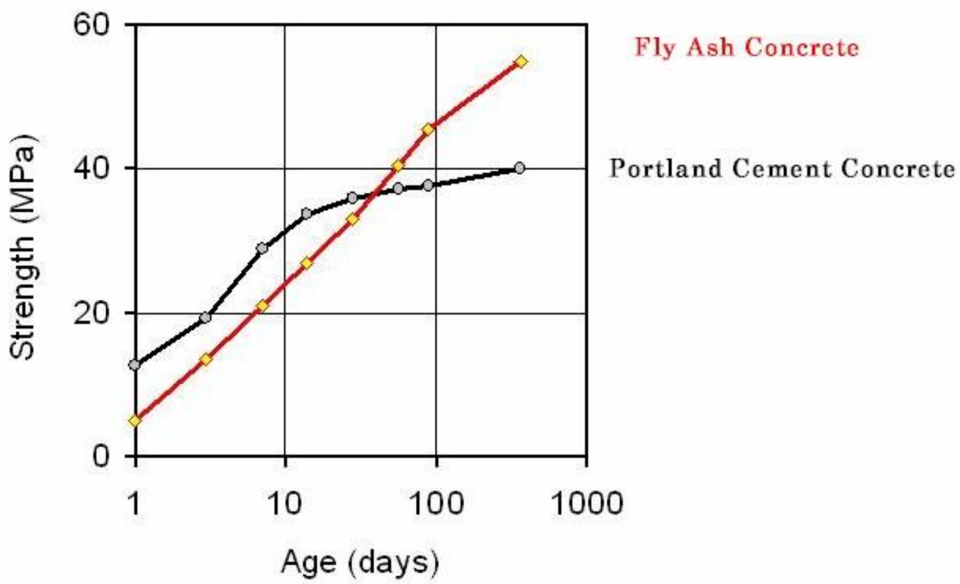


Figure 2.1 Strength development of fly ash concrete compared to normal concrete

2.3 Sustainability

Sustainability has an increasing trend globally and was creates in fulfilling the human needs through socio-economic and scientific development including preservation of the environment (Sage, 1998).Sustainable development is a contested concept with a wide range of meanings. It is embraced by big business, governments, social reformers and environmental activists (Bob Giddings, 2001). Without any option, sustainable development has become a necessity (World Energy Council, 2010). Sensitivity in sustainable growth is expanding around the world for decades. The UN Summit on Environment and Development in 1972, ‘Agenda 21’, the closing document of the UN ‘Earth Summit’ in 1992 in Rio de Janerio, trailed by other international and national meetings and conferences express the rising anxious for sustaining the environment for the future peers by introducing sustainable development concept (Parkin, 2000). A wide range of nongovernmental as well as governmental organizations have embraced sustainable as a new paradigm of development (Lele, 1991) .

In the perfect world model illustrated by (Chaharbaghi and Willis, 1999), there present a community that live in harmony and secured, inhale fresh air, consume clean water and eat clean food. They have livelihoods that allow them to enjoy life, raising healthy, contented and educated children. They leave behind them a stock of wealth comprising manmade and environmental assets for the next generation, no less than they inherited from the previous generation. The real world, however, is far from this ideal.

Sustainability is a process that distinguished of a progress or situation that can be preserving at a convinced level for an indefinite period. In environmental sense, refers to the possible permanence of human natural support systems, such as the planet's climatic system, agricultural, industrial, forestry, fisheries, and human. Sustainable development strategy includes three universal areas i.e. economical, environmental, and social. Concrete industry has adopting towards a sustainable development material in producing green concrete.

Sustainable construction refers to the construction of the environmental friendly building and infrastructure, sustainable expenditure refers to the expenditure of low carbon emission of concrete and sustainable concrete industry refers to the concrete industries sector that working towards sustainable industry model (Ashley, 2008).

Continuous economic growth, social community, cultural civilizing and scientific development is a sustainable dependant. Cautious awareness should focusing to the conservation of the earth's natural system in order to achieve the sustainable world progress. Associated with the accomplishment in increasing the technological also the economic development together with the conservation of the environmental and natural possessions has a link to sustainable development target. It is necessarily for concrete industrial sector to understood context of local circumstances such as scientific technologies, stakeholder traditions, capital and institutional systems in order to improve the sustainable policies (Henry & Kato, 2012).

As illustrated in Figure 2.2, sustainability is governed by three main pillars which are social, environmental and economic pillars. The recent awareness in green technology has aid to recently define environmental sustainability. It has been taking into attention that the environmental pillar of the sustainable development is solely in preserve the natural system. Towards conserving or preserving the reliability of the natural supports systems, environmental sustainable is also specifically focusing on its bio-geophysical element (Moldan, Janoušková, & Hák, 2012)

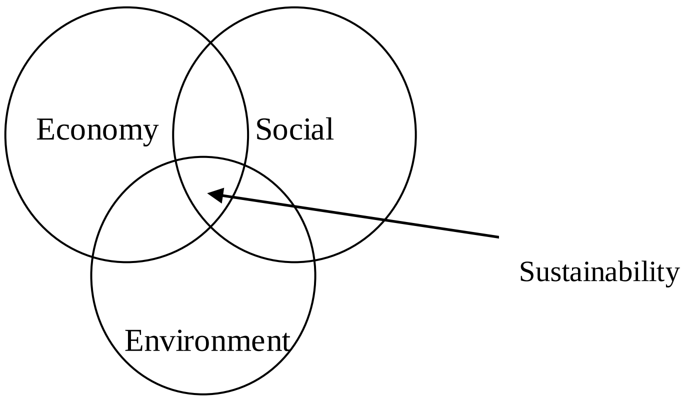


Figure 2.2 Ideas governing sustainability

2.3.1 Environmental Sustainability

Construction industrial sector is significantly influence the economic development of a country. Despite this encouraging outcome, it is necessarily to see the negative consequences towards the environment (Braga, de Brito, & Veiga, 2012). The energy usage has often been considered as influenced the environmental sustainability. Embodied energy that contain in the materials and products used in the construction of the structure also energy consumption throughout the service-life of the building includes in influenced the environmental sustainability. The exhaustion of natural assets also needs to be considered while the energy usage affected by other factors (Cement & Concrete Institute, 2011). (Khalfan, 2002) addresses the philosophy of environmental sustainability which to produce our natural system in a good or a better condition for future. For instance, without diminish the natural assets or destroy the natural environment, it is only considered as environmentally sustainable for human activities. In addition, supply expenditure has to be reduce, and materials consumed should a recycled materials or from renewable resources (produce without spoiling the environment and diminish the sources), Recycling waste streams should be support where energy should be preserved and energy provisions should be totally renewable and non-polluting technology.

The use of natural resources should be efficient, there should be the reduction of waste and contamination, the protection of natural diversity, emission control of green house gasses, smart control for road traffic, river quality, inhabitants of wild birds, produce less waste, effluent generation, sustainable development and construction, controlling emissions to environment, decrease hazard to health, utilization of renewable element material, remove of toxic substances, etc.

The major support which helps maintain the environmental sustainability mainly for the concrete industry is by using an industrial waste material, fly ash powder originates from thermal power plant has widely use by major industrial. It has been understood from numerous researches that cement and concrete industry produce the largest CO_2 emission (greenhouse gases emitted to the atmosphere in large amount which causes a global warming. (Don Wimpenny, 2009) asserts that concrete production accounts for approximately 5% of greenhouse gas emission worldwide. He affirms that the majority of these emissions derive from the cement binder which comes from cement manufacture. Asian region and worldwide has extensively utilize concrete as construction material for infrastructure development (Tony and Jenn, 2008). However, concrete industry is accountable for high release of carbon dioxide though they are main patrons of natural resources and energy. Thus leading to global warming which caused by the greenhouse gases. (Van den Heede & De Belie, 2012) denotes that the attempt to reduce CO_2 emission in concrete is by replacing the clinker content in the cement production with alternative waste material, by means of reducing the cement constituents in order to reduce the emission of carbon dioxide . Fly ashes that were originated from thermal power plants are recommended as the main substitutions for the clinker (Habert & Roussel, 2009).

Carbon footprint and the Carbon label are suggested to measure the carbon release of different products (Cagiao, Gómez, Doménech, Mainar, & Lanza, 2011). Carbon footprint define as the sum of greenhouse gas emissions that are produce directly and indirectly by any person, occasion, association or result expressed as mainly CO_2 emissions (Carbon trust, 2009). (Wiedman, T. and Minx, 2008) identify carbon footprint as "a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity that is directly and indirectly or is accumulated over the life stages of a product." Carbon footprints have recently drawn considerable attention in order to limit greenhouse gas emissions. Diverting construction wastes to recycle purpose is seen as a better way in reducing the CO_2 footprint by 5.9% (Chau, Hui, Ng, & Powell, 2012).

2.3.1.1 Carbon Index

As a result of human activities, carbon in the form of carbon dioxide (CO_2) is known as one of the major greenhouse gases that emitted to the atmosphere. The main contributor is from the fossil fuels burning also, land degradation such as mining and deforestation. CO_2-e is a measure for greenhouse emission. It is abbreviated for 'carbon dioxide equivalent' and is an internationally recognized. Six different types of greenhouse gases controlled by the Kyoto protocol includes carbon dioxide (CO_2), nitrous oxide (N_20), methane (CH_4) and a range of synthetic (industrial) gases including perfluorocarbons (PFC), hydrofluorocarbons (HFC) and sulphur hexafluoride (SF_6). Each of these gases has its own capability to heat the atmosphere which also known as global warming potential (GWP). While CO_2 is categorized as non effective greenhouse gas, nevertheless they are produced in a large quantities, this will influence the other greenhouse gases (Carbon Index, 2008)

Reporting greenhouse emission as they are corresponding to a given volume of CO_2 is known as CO_2-e. For instance, greenhouse emissions from a landfill of 100 tons of methane are recorded as 2,100 tons CO_2-e. By using CO_2-e as a measure of greenhouse emissions; it may tolerate us to evaluate the greenhouse effects from a wide range of greenhouse emission sources. Greenhouse gases (GHGs) are identical with global warming. In order to alleviate the impact of global warming, reducing energy consumption is necessarily. The universal Standard Assessment Procedure (SAP) is used to measure energy rating from energy-efficient buildings. The rating is ranging from 1 (poor) to 100 (good). Carbon index acts as a relative means of energy rating that estimate the quantity of carbon dioxide emitted. A carbon index of 8 is roughly equivalent to SAP's 1 (Carbon Index, 2008).

2.3.1.2 Carbon Footprint

The carbon footprint is a measurement system that computes accurately level of carbon emission. In order to set a target in measuring carbon level and to evaluate amongst other properties carbon footprint is a necessarily. These measurements will also allow maximizing energy effectiveness. Embodied carbon and operational carbon are incorporated in measurement carbon footprint in building. Process involved in deriving CO_2 such as materials production, transportation and site assembling, preservation and substitution, disassembly and decay are components of embodied carbon in a building. Operation of a building will always produce CO_2 carbon which also known as operational carbon. Material development and preparation, construction stage (including transportation), disposal or ongoing occupational emissions from resident and refurbishment and redevelopment would ideally a typical carbon footprint elements will consists of material improvement and research, construction progress, transportation, resident's dumping, and refurbishment and redevelopment (Carbon Index, 2008).

2.3.1.3 Embodied Carbon

(UNEP, 2007) reported that total carbon footprint of any construction project accounts for 13-18% of embodied carbon. By focusing on rising energy effectiveness to control operational carbon emissions, describe the rationale for the initiatives. The important of embodied carbon is explained by the more energy efficient are the buildings, will results for high fraction of a service life period for less-energy buildings.

A rising demand was noticed for proprietor and design engineer to be more concern of carbon footprint produces by their buildings. With the present awareness on energy effectiveness, they were cautious of the embodied energy and associated greenhouse emitted in their property. It will be much beneficial for quantity surveyors provide their cost rate schedule with an appropriate carbon ranking which may categorize elements of a building. These may provide results such as maximum carbon costs and in turn for the value engineer to alleviate the hazard of acquire more carbon footprint. These will result for an energy-proficient and carbon-efficient building.

Various variables involved in calculating embodied carbon have a tendency to influence the carbon intensity of products. These include the producer, transportation, principal power supply and the amount of waste or salvaging. Nevertheless, products development that are more carbon-demanding than others, such as cement, aluminium and glass, thus it is not an obligatory to compute the total carbon footprint of a project, as several element will having an insignificant impact and present inadequate possibility for alleviation. Concerning the ideology of important point rate approximation of the carbon estimation and adding an allocation for the residue may be a realistic method that focuses on the most carbon-intense and expansively used elements (Wright & Rowlinson, 2007).

2.3.2 Economical Sustainability

Concept of sustainability involves an economical consideration. Whilst a business it permit for development for an indefinite period time, it is consider sustainably control (Peris Mora, 2007). The financial growth of a country is significantly influenced by its construction sector. While the economic expansion is greatly boost the gross profit of a county, it is necessarily to consider the adverse effect on the environmental (Braga et al., 2012). Different system for occupying active capital optimally so that an accountable and valuable balance can be accomplished for an indefinite period time defines the economic sustainability. In a business perception, economic sustainability engaged by the various property of the company resourcefully to allocate it to maintain operation beneficially by time (businessdictionary, 2013). Direct, indirect and induced effects are the factors in aiding towards total economic. The direct element is the value of business produce within the concrete industrial sector; indirect effects are from provider businesses to the cement and concrete industry, while induced effects are the cost of expenses from the profits by cement and concrete manufacturer (sustainable concrete, 2013).

Economic sustainability consists of various sub-themes such as human asset, aggressive financial system, career opportunities, vibrant local economy, available services which reduce the use of car, formation of new markets and opportunities for sales expansion, cost reduction through efficiency improvements and reduced energy and raw material inputs, and the creation of additional added value. In order to achieve the potential sub-themes, sustainable growth should not be acquire more expenses than required (Khalfan, 2002). (Parkin, 2000) lists the model of economic sustainability that includes five capitals, which actually represent all the possessions existing to a community in accomplishing sustainable growth. These five capitals are natural capital, human capital, social capital, manufacturing capital, and financial capital. According to (Parkin, 2000) each capital is corresponding to the contribution in the economic terminology which may be invested or not, and capital that anticipate a positive turnover.

Environmental or ecological capital are consigned to natural capital which represent the demand of environmentally provided property which includes renewable and non-renewable resources, and services such as the natural waste processing system. Human capital allow an individual to think rationally of themselves, others and to contribute well in the community and in return will contribute efficiently towards its welfare and prosperity. Wellbeing, education, talent, enthusiasm and religious simplicity are the components in human capital. Diverse supportive systems and organisational frameworks in which people use to stay and built career together, such as family unit, societies, government, trade industry, schools, trade unions, and voluntary groups defines the social capital. The whole human-constructed facilities that are already exist included in the manufacturing capital such as the equipment, machinery, infrastructure, and buildings. Financial capital has no inherent rate whether in shares, bonds or banknotes. Its importance is entirely representative of natural, human, social or manufactured capital. Financial capital is truly significant, as it replicate the dynamic influence of the others capital, and allow them to be possess or operate (Parkin, 2000).

The economical sustainability is often having less interest mostly in the urbanized countries, but is regularly critical to accomplish the aim of sustainable growth. The global discrimination in expenditure of capital is surprising. Economical and environmental sustainability are strongly associated to each other. Environmental deficiency arise while individuals are belligerent to get the resources that necessary for their life (food, water, shelter, etc.), and it is foreseeable that the fundamental economical resist might get preference over environmental sustainability. Conversely, environment deterioration will deteriorate the economic inequality, such as diseases related to the lack of clean water are a important cause of deficiency (Struble & Godfrey, 2004).

Recycling has always seen as the best approach in minimizing and optimizing. It has been addressed by (Tam, 2008), that by recycling concrete as an aggregate for new concrete invention, it can at least afford a price-efficient scheme for the sector and that it subsequently helps in saving the environment. Self-compacting concrete (scc) provides a benefit to the economy since the casting of scc demands less manpower compared to the conventional concrete, for this reason, it will assist in reducing the costs and subsequently increase the productivity. As an addition, the value of concrete is enhanced by larger voids and granular inhomogeneities can be avoided. This decrease the necessitate of rehabilitations process, which resulting in better efficiency (Damtoft, Lukasik, Herfort, Sorrentino, & Gartner, 2008).

2.4 Approaches Towards Sustainable : Green Technology

Buildings have a remarkable effect on the environmental inclusive during production and all over during service life. "Green building" is defined as compilation of land-use, designing the building, and building construction plan that will lessen the environmental impacts. The green building strategies includes holistic approach during design of structures. Resources to produce building such as raw materials, fuels or the contribution of the users need to be carefully determined in order to produce a sustainable building. Several contradictory issues and standards involve in producing a green buildings. Any design choice will cause to environmental implications. Evaluation for green buildings can be categories into:

• Reducing embodied energy and resource depletion;

• Reducing energy in use;

• Minimising external pollution and environmental damage; and

• Minimising internal pollution and damage to health

Building in good quality; long service-life, economic, easy to operate and maintain and also offer better resident contentment than any typical developments are the criteria of most green building. Promises in giving good services, better design ideas, new technology approaches, and excellent applications are the most significant approaches than any high construction resources (Khalfan, 2002).

2.5 Approaches in Measuring CO_2 footprint in Concrete

While there are many studies conducted for measuring CO_2 footprint in the cement industry, very few have focused on measuring the CO_2 footprint of concrete production. Approaches in measuring CO_2 footprint in concrete were divided into two main approaches which are estimating CO_2 footprint based on inventory data and entity organisation. Process involved in estimating the CO_2 foot-print in concrete production will also be reviewed. It was observed that each country has a different methodology in estimating, depending on their accessible sources.

2.5.1 Estimating based to Inventories Data

(Henry et al., 2011) investigate the consequences by using different quantity of low-grade recycled aggregates in concrete with addition of mineral admixtures on mechanical and ecological properties. Environmental performance was determined by using inventory data as shown in Figure 2.3 for CO_2 footprints of concrete-making materials in Japan provided by (Japan Society of Civil Engineers, JSCE 2006) in measuring their CO_2 footprint designed from the mix proportions. The potential of reducing CO_2 when using fly ash and ground granulated blast furnace slag was studied.

The mix constituent comprises three water-binder ratios (0.3, 0.375, and 0.45), two binder combinations (C50%-FA 50% and C50%-FA%-BS25%), and three recycled aggregate replacement ratios (0%, 50%, and 100%). Environmental impact assessment was determined with the usage 50% of fly ash yet with low water-binder ratios and higher binder, CO_2 foot-print were reduced compare to the control mix series. Figure 2.4 shows mixes with different binder ratios versus CO_2 footprint (kg-CO_2/m^3).

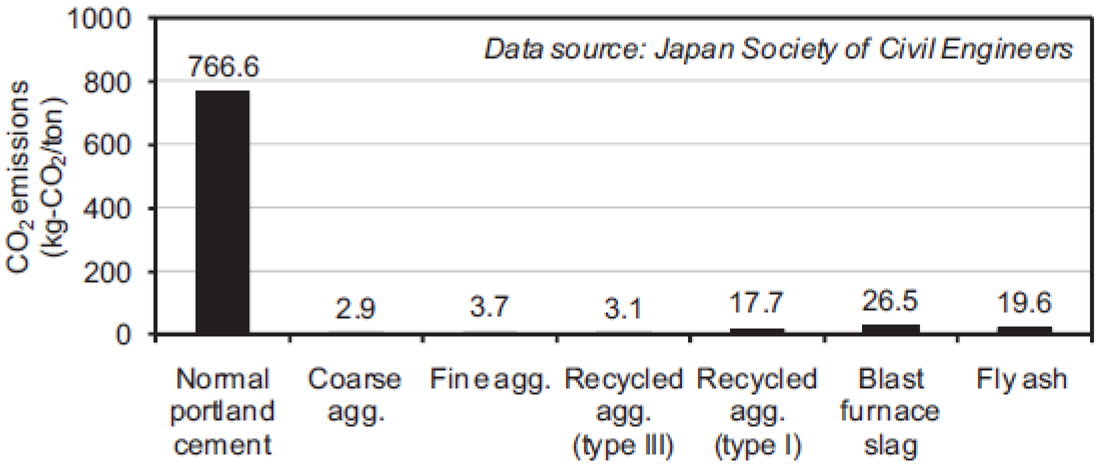


Figure 2.3 CO_2 footprint of concrete making materials in Japan (Henry et al., 2011)

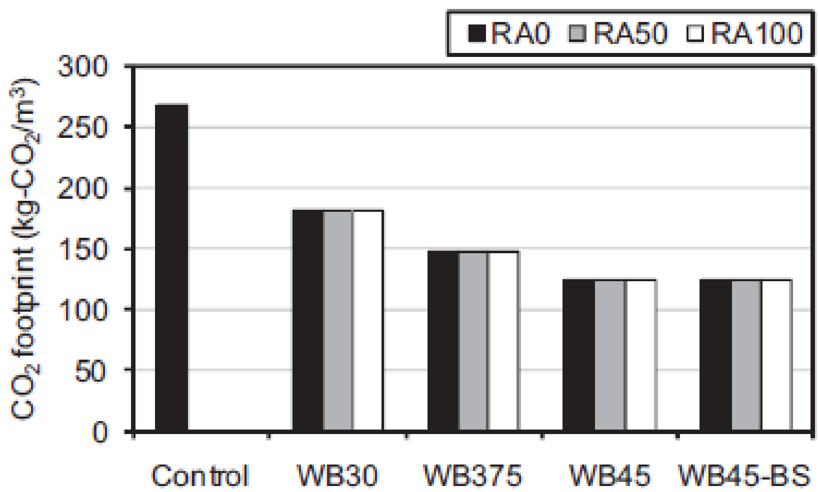


Figure 2.4 Calculated CO_2 (Henry et al., 2011)

Other researchers which employ inventory data in estimating the CO_2 footprint is (Karim et al., 2011). Data provided by (Ehrenberg & Geiseler, 1997) show that CEM I (OPC) produces 1011 kg-CO_2/tonne. When replaced with 30% slag it gives 730 kg-CO_2/tonne, if replaced with 50% slag it gives 539 kg-CO_2/tonne. Meanwhile with the replacement level of 75% slag it gives 300 kg-CO_2/tonne. From the values gathered, the results are undeniably positive. With high replacement level of slag, it could reduce the CO_2 footprint of a concrete itself. The data on their CO_2 footprint are summarized in Table 2.1.

Table 2.1 CO_2 footprint from cement production (Karim et al., 2011)

Type	Amount (kg/tonne) (% CO_2 emission)	Reference
CEM I	1011 (100)	
CEM IIB-S (30% slag)	730 (72.2)	(Ehrenberg & Geiseler, 1997)
CEM III/A (50% slag, GGBS)	539 (53.3)	
CEM III/B (75% slag, GGBS)	300 (29.7)	

(Edward, 2010) introduces a South African model for the determination of carbon dioxide equivalent (CO_2-e) footprint related to the production of a cubic meter of concrete. Based on his research, the carbon dioxide equivalent (CO_2-e) footprint was gathered based on the components of a concrete mix and their related footprints. Since most of the footprints result from the energy consumption, thus his study was primarily focusing on quantifying the energy consumption of each activity involved. Results produced are illustrated in Table 2.2.

Table 2.2 Specific CO_2 equivalent footprint per concrete constituent (Edward, 2010)

Element	Specific Emission	Unit
Aggregate	5	kg-CO_2e/tonne
Cement CEM I	818	kg-CO_2e/tonne
Fly Ash	2	kg-CO_2e/tonne
Ground Granulated Blast Slag (GGBS)	128	kg-CO_2e/tonne
Admixtures	220	kg-CO_2e/tonne
In-Situ Concrete	9	kg-CO_2e/tonne
Pre-Cast	18	kg-CO_2e/tonne

2.5.2 Estimating based to reports by Entity Organisation

Another approach in estimating CO_2 footprint in concrete is by using carbon footprint data from cement manufacturers which are audited by an accredited body. In Malaysia, the Standards & Industrial Research Institute of Malaysia (SIRIM) is responsible in promoting and undertaking scientific and industrial research. The following Table 2.3 reports on the footprint of product from YTL Cement, Westport Plant, Malaysia.

Table 2.3 CO_2 emission in various types of blended cements (YTL Cement Malaysia, 2011)

Product (Westport Plant)	Emission (kg-CO_2/mt)
Ground Granulated Blastfurnace Slag (GGBS)	50
Slagcem 70 (SC 70) (CEM III/B)	290
Portland Composite Cement (CEM II/B-M)	570
Mascem 25 (MC 25) (CEM II/B-V)	645
Slagcem 60 (SC 60) (CEM III/A)	370
Composite Cement (CEM V/A)	530

The collaboration between the YTL Cement Malaysia with the Standards & Industrial Research Institute of Malaysia (SIRIM) produce significant data and this is comparable with other available data. Elements of concrete were studied and results produced are illustrated in Table 2.4

Table 2.4 CO_2 emission for concrete constituent

Element	Emission	Unit
Aggregate	4	kg-CO_2/tonne
Cement CEM I	1000	kg-CO_2/tonne
Fly Ash	50	kg-CO_2/tonne
Ground Granulated Blast Slag (GGBS)	50	kg-CO_2/tonne
Admixtures	0.2	kg-CO_2/tonne

Table 2.5 below shows the summary of available data on CO_2 emission estimation based on different countries and contexts. From the figure, it clearly indicates that South Africa and the United Kingdom show a similarity in their end value of CO_2 footprint for aggregate, meanwhile CEM I show comparable values. Japan marginally results in the lowest CO_2 footprint when compared to the other case studies.

Table 2.5 Overall CO_2 emission comparisons

Element	Specific Emission				
	Malaysia	Japan	Australia	United Kingdom	South Africa
Aggregate	4	2.9	32	4	5
Cement CEM I	1000	766.6	822	819	818
Fly Ash	50	19.6	27	4	2
GGBS	50	26.5	143	52	128
In-Situ Concrete	-	-	12	4	9
Admixtures	0.2	-	-	380	220
Pre-Cast	-	-	-	14	18
Units	kg-CO /tonne		kg-CO e/tonne		

2.6 Methods Involved in Measuring CO_2 emission in Concrete

Methods involved in quantifying CO_2 emission in concrete are dependent on the manufacturing and also the placement of the concrete. Energy input which leads to CO_2 emissions includes transportation, concrete mixing and placement of concrete. Basis for evaluating concrete based on their CO_2 emissions was carried by (Flower & Sanjayan, 2007). They discover that the emission of each constituent of materials of concrete including cement, coarse aggregate, fine aggregate and also mineral admixture such as fly ash and ground granulated blast furnace slag (ggbfs). Chemical admixtures which are referred as superplasticizer, accelerator, water reducer and retarder in the concrete mixture produced were also reported. However they were justifiably negligible since they have a small contribution due to insignificantly low CO_2 emission. The energy source processes involved in the production of the constituent materials include transportation, batching, and placement, electricity energy, and fuel consumption have also been established.

(Edward, 2010) was assigned by the Cement and Concrete Institute to develop a model specifically for the evaluating carbon dioxide equivalent (CO_2-e) emissions of a cubic metre concrete in South Africa. It should be noted that CO_2-e (CO_2 equivalents) is applied as the unit, that is regulate to comprise the global warming effects for CH_4 or N_2O emitted from a similar procedure. When determining the carbon emissions of any process, a set of applicable rules need to be used. The set of rules and principles used to define the emissions is the internationally recognised GHG protocol (Greenhouse Gas Protocol). This protocol is also used by the WBCSD (World Business Council for Sustainable Development) in the approved cement emission model. The protocol defines three categories of emission sources namely Scope 1 (direct) that refers to direct GHG emissions from sources that are owned or controlled by the reporting entity. Scope 2 or (indirect) emissions are the consequence of the activities of the reporting entity, but occurring at sources owned or controlled by another entity. They include GHG emissions resulting from the consumption of the purchased electricity, heat and steam and Scope 3 (other indirect) depending on internal reporting requirements, preset reporting standards and CDP requirements. Organisational activities resulting in other indirect emissions include: staff commuting, final production transportation by a third party and outsourced activities. Method involved in measuring CO_2 emission in concrete production will be discussed in two methods of estimation specifically the raw materials and the scopes.

(Cagiao et al., 2011) have highlighted that in order to calculate the material footprint, it is important to allocate a consumption category to each item of the organization's financial accounts as listed in Table 2.6.

Table 2.6 CO_2 emissions associated with admixture manufacture (Flower & Sanjayan, 2007)

Admixture Type	Primary raw material	Production energy (kWh/L)	CO_2 Emissions (t CO_2-e/L)
Superplasticizer	Polycarboxylate	0.0037	5.2×10^{-6}
Set accelerating	Calcium nitrate	0.0380	53×10^{-6}
Mid range water reducing	Calcium nitrate	0.0290	40×10^{-6}
Water reducing	Lignin	0.0016	2.2×10^{-6}

2.6.1 Emission Due to Coarse Aggregates

(BS 882 : 1992) defines aggregate as a granular material obtained by processing natural materials' aggregate mainly retained on a 5.0 mm BS 410 test sieve and containing no more finer material than is permitted for the various sizes in this specification. The coarse aggregate may be described as gravel that is uncrushed which results from the natural disintegration of rock, crushed gravel produced by crushing the gravel, partially crushed gravel produced from a mixture of crushed and uncrushed gravel, crushed rock produced by crushing the rock and blended coarse aggregate produced by the controlled blending of gravel and crushed rock.

The production of aggregate does not have a large significant CO_2 emissions related to it. Nevertheless, other environmental impacts that are not related to GHG emissions should be managed efficiently, as suggested by (Schuurmans, Rouwette, Vonk, Broers, Rijnsburger & Pietersen, 2005) Study by (Edward, 2010) and they indicate that scopes that are involved in the production of aggregates are Scope 1 and Scope 2 . Scope 1 consists of explosive and on-site vehicles. Explosives are used for the blasting of geological reserve meanwhile on site vehicles result from fuel used by onsite vehicles; mainly for loading and hauling processes. Scope 2 consists solely by the electricity consumption during the crushing operations at mostly electricity-sourced quarries. (Flower & Sanjayan, 2007) have specified in their study, which process involves measuring the emission of CO_2 due to the coarse aggregate. The first process is to change the size of the rock into medium size boulders and medium size rocks are impacted by the blasting process from the explosive technique. The rubble is then removed by diesel-powered excavators and haulers. It was then dumped into electric equipment for crushing and screening. Finally diesel powered haulers move the final graded products into stockpiles. Information such as the fuel, electricity and explosives were gathered through the invoices, and also site sales figures. Data from fuel, electricity and explosives are used to calculate the amount of CO_2 produced per tonne of aggregate at the site. Emission factors (t/CO_2-e/tonne) were first determined which include the average contribution from the transportation quarry to the concrete batching plant.

Electricity is found as a major contributor and it is accountable for large CO_2 emissions for every category of aggregate. This explains that the crushing procedure is the most important component of the coarse aggregate production. On-site blasting, excavation and hauling, in addition to off-site transport encompass not more that 25% of the total emissions for coarse aggregates. Explosives process accounts for less percentage (<0.25%) of the total emissions. To accomplish low environmental impact in aggregates production, the crushing process needs to be developed. Smart explosives technology during blasting process can diminish the requirement on the electrical crushing equipment by explosive the rock into smaller fraction prior to crushing. Another approach seeking to lower electricity demands during the crushing process is by maintaining the frequency in the maintenance crushing equipment. In addition, the replacement of aged and unproductive machinery will helps in lowering energy demands.

CO_2 emission associated with aggregates production produced by (Edward, 2010) as illustrated in Figure 2.5. From the figure, 64% of the aggregate production was dominated by Scope 2 that refers to the electric consumption during the production of aggregates. Electric consumption was found to be the dominant factor during the crushing process. By percentage, 36% was covered by Scope 1 that refers to explosives and on-site vehicles.

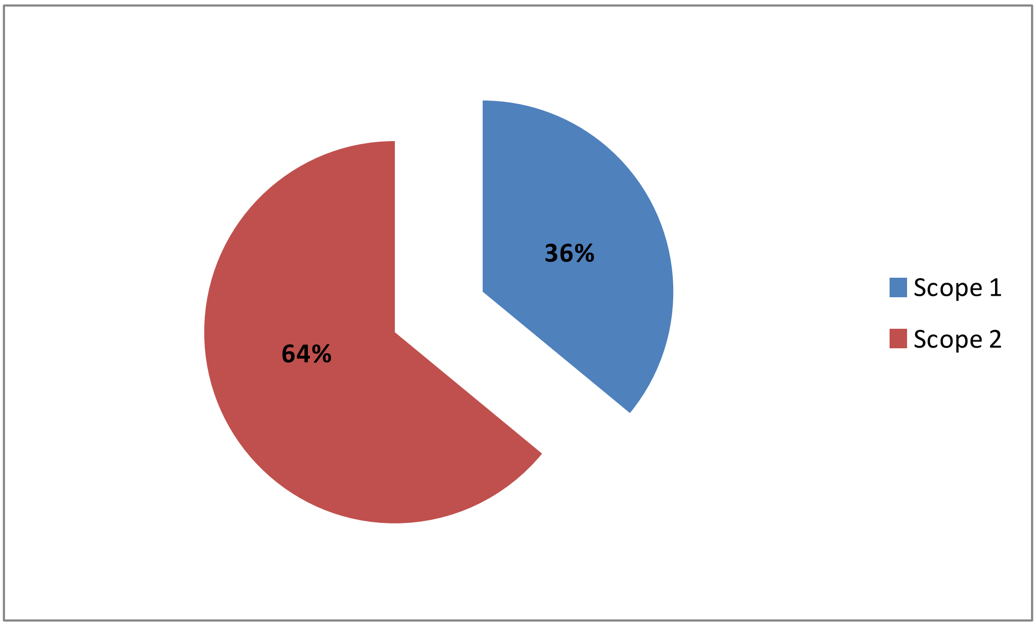


Figure 2.5 CO_2 emission associated with aggregates production (Edward, 2010)

2.6.2 Emission Due to Fine Aggregate

Fine aggregate is an aggregate that is mainly passing a 5.0 mm (BS 410, 2000) test sieve and containing no more coarser material than is permitted for the various grading in the specification (BS 882 : 1992). Sand may be described as uncrushed or partially crushed. Uncrushed sand is sand that is originated from the natural disintegration of rock. Partially crushed sand is the sand that produced from a mixture of uncrushed sand and crushed sand resulting from the crushing of associated particles during product processing. Crushed gravel sand is the sand that is produced by crushing the gravel. Crushed rock sand is the sand that is produced by crushing the rock. Blended sand is the sand that is produced by the controlled blending of two or more of the types of sand.

(Flower & Sanjayan, 2007) investigate the emission due to fine aggregates by using raw sand. The raw sand is strip-mined by excavators and loaded into a hauler which is then dumped and it will be washed into pumpable slurry and piped to the grading plant. The sand will be graded into standard grades by using electric vibrating screens filter, which are then stockpiled. A six-month data for energy consumption and total productivity audited from a quarry were compiled. The emission factor which is the amount of CO_2 released during the production and subsequent transport of one tonne of concrete-sand is found to be 0.0139 t CO_2-e/tonne. 40% of the figure is for basalt coarse aggregate, and 30% of the figure for granite coarse aggregate. The crushing procedure is having insufficient data of difference between the emissions of fine and coarse aggregates.

Diesel and electricity contribute almost equal percentage to the CO_2 emissions from the production and transport of fine aggregates as illustrated in Figure 2.6. The diesel is consumed by the strip mining process and on off-site transportations. The effectiveness of mentioned procedure is basically exaggerated by the quality of the machinery equipment. Exchange of old excavators and haulers will assist in saving fuel and efficiency, and furthermore will lower the CO_2 emissions. Electricity is consumed by the pumping and grading equipment. The emissions associated with these processes are mostly being fix values. Regularly savings and relocating the screening plant closer to the source of the slurry is the alternatives for the process. However, the emissions associated with moving the equipment should be assessed. In general, the sand mining process is fairly well established, and intentionally or otherwise, is already organised to generate minimal CO_2.

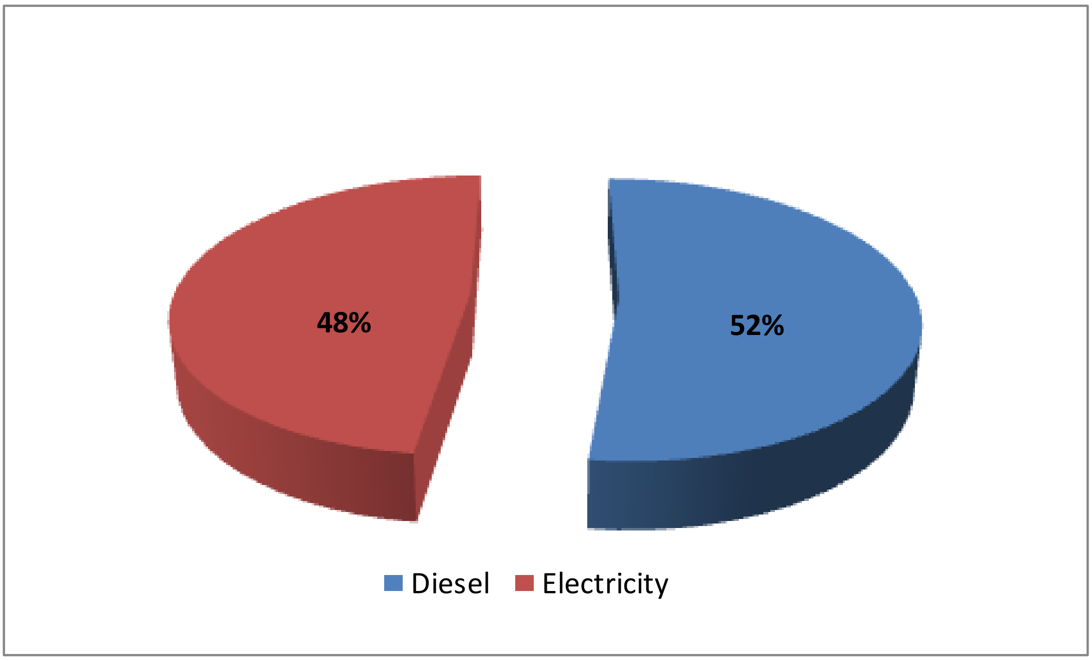


Figure 2.6 CO_2 emission breakdown of fine aggregates (Flower & Sanjayan, 2007)

2.6.3 Emission Due to Cement Production

Cement production is the main contributor to the emission of CO_2 into the environment. Environmental impacts associated with the cement production have attracted great interest among researchers in recent times. Decomposition of limestone is an essential process in the Portland cement production in cement kiln.

Cement kiln dust (CKD), a bypass dust, is generated in large quantities during the production of Portland cement. Cement kiln dust is a fine powdery material similar in appearance to the Portland cement. It is composed of micron-sized particles collected in the control devices (e.g. cyclone, bag house, or electrostatic precipitator) during the production of cement clinker. Based on the preparation of the feed material (a composite of different raw materials) prior to calcination, cement kilns are classified as either wet process, which take feed materials in a slurry form containing 30–40% water, or dry process kilns, which accept feed material in dry-grounded form. Modern cement plants favor the dry process which is more energy-efficient than the wet process cement kilns. In both of these processes, cement kiln dust can be collected in two ways: (i) part of the dust can be separated and returned to the kiln from the dust collection system (cyclone) close to the kiln, or (ii)the total quantity of dust generated can be recycled or discarded. In general, CKD is a very heterogenous mix both in terms of the chemistry and particulate size, and chemical composition of CKD depends upon the raw materials, fuels, kiln type, overall equipment layout, and type of cement being used. The concentration of free lime, sulfates and alkalies in CKD is mainly dependent upon the size of particles collected near to the kiln. Coarser particles of CKD contain high content of free lime while the fine particles usually exhibit higher concentration of sulfates and alkalies and lower lime content. Analysis of cement kiln dust with X-ray diffraction studies reveals that limestone ($CaCO_3$) is the major component of CKD whereas, quartz (SiO_4) together with small quantity of gypsum ($CaSO_4$), sodium chloride (NaCl), arcanite (K_2SO_4), spurite[$2(C_2S)\cdot CaCO_3$] and sulfospurite [$2(C_2S)\cdot CaSO_4$] constitutes the minor component (Siddique & Rajor, 2012). The chemical reaction for this process is:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad \text{(Equation 2.1)}$$

This process releases 0.5 ton of CO_2 for every ton of lime (CaO) produced. The high energy consumption of the kiln produces additional CO_2 emissions which are added to obtain the total emissions during Portland cement manufacture. A part of the CO_2 emissions due to the decomposition of limestone is re-absorbed from the atmosphere by concrete due to a chemical reaction called carbonation. The free lime, $Ca(OH)_2$, in the pores of the concrete reacts with the atmospheric CO_2 and produces $CaCO_3$. This chemical reaction is commonly described as the carbonation of concrete.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad \text{(Equation 2.2)}$$

Process involved in the hardening of concrete is sometimes mistakenly referred as the carbonation reaction. The hardening of concrete is an entirely different reaction involving the hydration of cement which does not have any CO_2 implications. The carbonation of concrete structures only occurs near the surface of the concrete. For a typical concrete structure, the carbonation depth would be about 20 mm from the surface after 50 years. Furthermore, the major part of the CaO in cement is tied up as part of the hardened concrete in the form of calcium silicate hydrates which are not available for carbonation. Therefore, the re-absorption of CO_2 by concrete during its lifetime would only be a very small proportion, and may not be considered in the calculation of CO_2 emission.

Emissions resulting from the cement production that have been calculated using the WBCSD (World Business Council for Sustainable Development) cement tool based on the GHG Protocol are the most reliable. A study by (Edward, 2010) addresses the fact that the main emission sources related to cement production, identified by the GHG Protocol (2004) listed Scope 1, 2 and 3 in calculating the CO_2 emission. Scope 1 consists of calcinations or pyro-processing, fuel burning, on-site fuels and explosives. Calcination involves the process of the decomposition of limestone, which is generally the largest source of GHG emissions during the cement production. Calcination can be expressed by the equation:

$$CaCO_3 + heat \longrightarrow CaO + CO_2 \qquad \text{(Equation 2.3)}$$

Fuel burning during pyro-processing requires flame temperatures above 2000°C in the kiln. The kilns are primarily fired by coal and emissions that can be expressed by the equation:

$$C + O_2 \longrightarrow CO_2 \qquad \text{(Equation 2.4)}$$

Depending on the raw materials and the actual production process, a cement production plant can consume fuel at a rate between 3,200 and 5,500 Mega joules per ton (MJ/t) of clinker under normal conditions. On site fuel generally comes from on site transport in the form of quarry haul trucks, front end loaders and personnel transport. In addition, fuels are also sometimes used to dry coal and other raw materials, depending on the plant design.

An explosive is a chemical material that, under the influence of thermal or mechanical shock, decomposes extremely rapidly and spontaneously with the evolution of large amounts of heat and gas. Since an adequate supply of oxygen cannot be drawn from the air, a source of oxygen must be incorporated into the explosive mixture. Some explosives, such as trinitrotoluene (TNT), are single chemical species, but most explosives are mixtures of several ingredients. As in other combustion reactions, a deficiency of oxygen favours the formation of carbon monoxide and unburned organic compounds and produces little, if any, nitrogen oxides. An excess of oxygen causes more nitrogen oxides and less carbon monoxide and other unburned organics. For ammonium nitrate and fuel oil (ANFO) mixtures, a fuel oil content of more than 5.5 percent creates a deficiency of oxygen.

The emissions from explosives detonation are influenced by many factors such as explosive composition, product expansion, method of priming, length of charge, and confinement. These factors are difficult to measure and control in the field and are almost impossible to duplicate in a laboratory test facilities. With the exception of a few studies in underground mines, most studies have been performed in laboratory test chambers that differ substantially from the actual environment. Any estimates of emissions from explosives use must be regarded as approximations.

Explosives are used for the blasting of limestone reserves. The cement protocol deems these emissions as immaterial, relative to the other emission sources. It should be noted that emissions from explosives have been included in this study for transparency. Scope 2 emissions involves solely on electricity consumption that is generally split and reported for various production departments of a cement plant production with the raw milling, kiln and finish milling consuming the most highly electric consumption. Cement plants are large energy intensive industrial sites. Hence there is a high CO_{2}-e emission factor associated with electricity consumption locally.

Scope 3 involves transportation and carbonation processes. Transportation is generally constituted by off-site transportation of raw or intermediate products by road and rail trucks from an initial processing plant to a final processing plant. Transportation does not normally have a significant impact on the total CO_2 emissions of cement production. Transportation emissions occur during the delivery of raw materials to the plant as well as during the delivery of processed products to the customer. It is logical to examine the Green House Gas Protocol (GHG Protocol) as well as other associated documentation to determine industry standards.

2.6.4 Emission Due to Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS)

Emissions involve for production of fly ash and ground granulated blast furnace slag purely lies on activities conducted during the initial production, including capture, milling, refining and transportation of 100 km processes. (Flower & Sanjayan, 2007) have used an emission factor for fly ash at 0.027 t CO_2-e/tonne. Meanwhile, the emission factor adopted for ground granulated blast furnace slag (ggbfs) was at 0.143 t CO_2-e/tonne. Both fly ash and ground granulated blast furnace slag are by-products of industries (burning coal and producing steel respectively) which would operate regardless of the production of these useful materials.

Concrete often contains admixtures in order to enhance early age properties, workability and strength development characteristics. Determination of CO_2 emission by fly ash as determined by (Edward, 2010) includes scope 1 and 2 calculation. Scope 1 (direct) emissions result from fuel used by on-site vehicles. Scope 2 involves the electricity consumption during the production of fly ash. Generally fly ash that is a by product from coal combustion from thermal power plant needs to be classified to provide a quality controlled material for use in cement. This classification process involves the use of electricity to operate. Figure 2.7 shows CO_2 emission associated with fly ash production. From the figure, 99% of fly ash production was dominated by Scope 2 which refers to electric consumption.

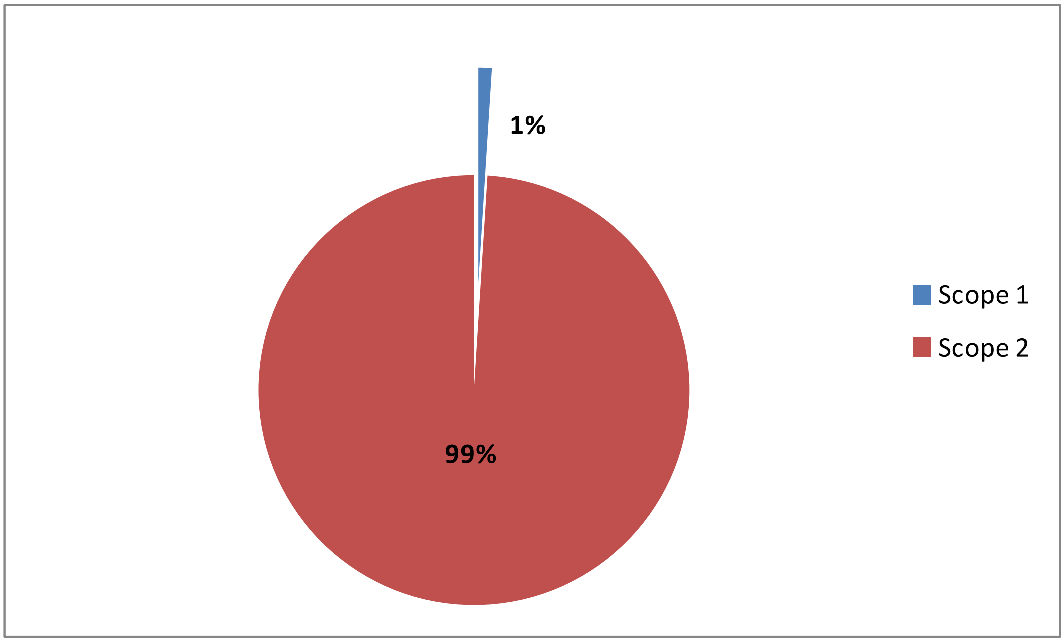


Figure 2.7 CO_2 emission associated with fly ash production (Edward, 2010)

2.6.5 Emission Due to Concrete Batching, Transport and Placement of Concrete

Emissions due to concrete batching, transport and placement of concrete are also investigated by (Flower & Sanjayan, 2007). Concrete batching is generally conducted at plants located at various strategic positions around a city or town in order to minimise transportation time. Raw materials are mixed in elevated bins and placed directly into concrete trucks for final transportation. This process is primarily powered by electricity, with small amounts of other fuels used on each site by small excavators used to move raw materials, etc. The energy consumption and production levels of six different concrete batching plants were audited over a six-month period. The average CO_2 emissions due to batching per cubic metre of concrete produced were found to be 0.0033t CO_2-e/m_3. Figure 2.8 shows the contributions of each energy source to the total CO_2 emissions.

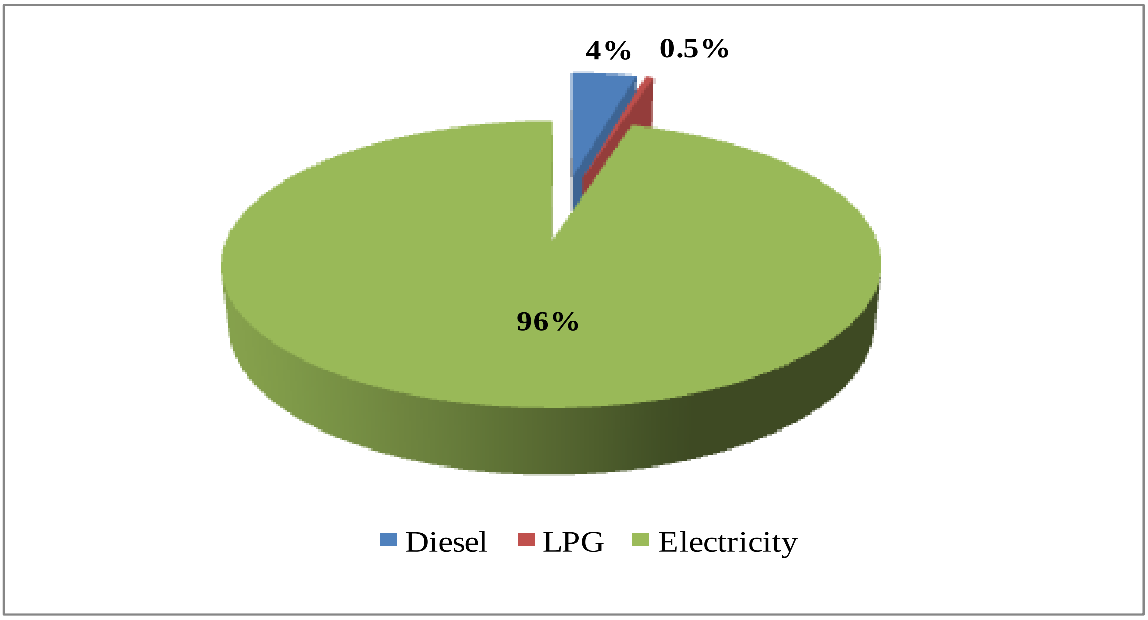


Figure 2.8 Concrete batching CO_2 emission breakdowns (Flower & Sanjayan, 2007)

From the figure, electric mixing equipment is the most significant contributor to the emissions generated by concrete batching. By commissioning independent electrical contractors to report on the efficiency of batching equipment and making improvements, it has been demonstrated by concrete manufacturers that substantial improvements can be made to the efficiency of the batching equipment. Ageing equipment often contains inefficient wiring and switches. Often equipment is left running by old switching equipment during zero load cycles when it could be paused. Thermal losses in poorly planned or low quality wiring can be reduced via replacement. The installation of high efficiency motors can reduce energy demands substantially. However, it should be noted that relative to other components of the concrete production process, the amount of CO_2 released through batching activities is fairly low, so it may be more critical to spend money on upgrading other more critical processes.

It is well known that transportation during batching of concrete from batching plant to construction sites consumes large amounts of diesel fuel. An average amount of fuel consumed per cubic metre of concrete transported was found to be 3.1 l/m^3, which was found to be responsible for 0.009t CO_2-e/m^3, data was gathered from trucking records taken over a five month period. Figures include return trips, since the total fuel spending for the entire fleet of trucks was used. It was presume that the distances trip were average for urban area.

Concrete placement activities such as pumping, compacting and finishing require usage of liquid fuels. The amount of diesel consumed to pump one cubic metre of concrete was found to be approximately 1.5 l/m^3, found by a survey of local pumping companies. The amounts of fuel required by other placement activities were impractical to precisely counted, due to the insufficient records and inconsistency between sites. Concrete that were poured using craned is also impossible to count. Thus, the value of 1.5 l/m^3 was doubled to cater for other concrete pouring activities. 3 l/m^3 was presumed for diesel fuel, and was found to be accountable for the release of 0.009t CO_2-e/m^3.

2.7 Previous Research Work in Estimating Carbon Footprint in Concrete

Few researchers made an attempt to measure the CO_2 footprint in concrete. (Flower & Sanjayan, 2007) measure the CO_2 emissions related to concrete producers and concrete arrangement in the Australian context. The life cycle inventory data was gathered from quarries, batching plants and few other known sources. Equivalent CO_2 emissions were presented as the final result, and the possible of fly ash and ground granulated blast furnace slag (ggbfs) to decrease the emission rate was also examined and presented. They also display a concrete CO_2 emissions system diagram shown in Figure 2.9.

(Yang, Song, & Song, 2013) in their research made an evaluation procedure from cradle to pre-construction by using an individual incorporation consists of material, production, curing, and transportation phases for estimating the CO_2 reduction of alkali-activated (AA) concrete. In their findings, the reduction rate of CO_2 emission of AA concrete compared to normal concrete generally ranges from 55 and 75%. (Cyr, Trinh, Husson, & Casaux-Ginestet, 2013) reported on a possibility in evaluating relevance of utilizing metakaolin (MK) in grout purposely for soil nailing.

By adopting few databases from known databases sources, carbon footprint was measured by calculating CO_2 emitted of each individual constituents. By using few data sets from known databases, the transportation of the binder was considered. They have learned that by using MK it permit a large reduction of CO_2 emission in contrast to mortar mixture containing only OPC. CO_2 emission decreases strongly with 40%, 50% and 60% replacement of MK leading to 36%, 45% and 54%, reduction of CO_2 respectively compared to 100% Portland cement.

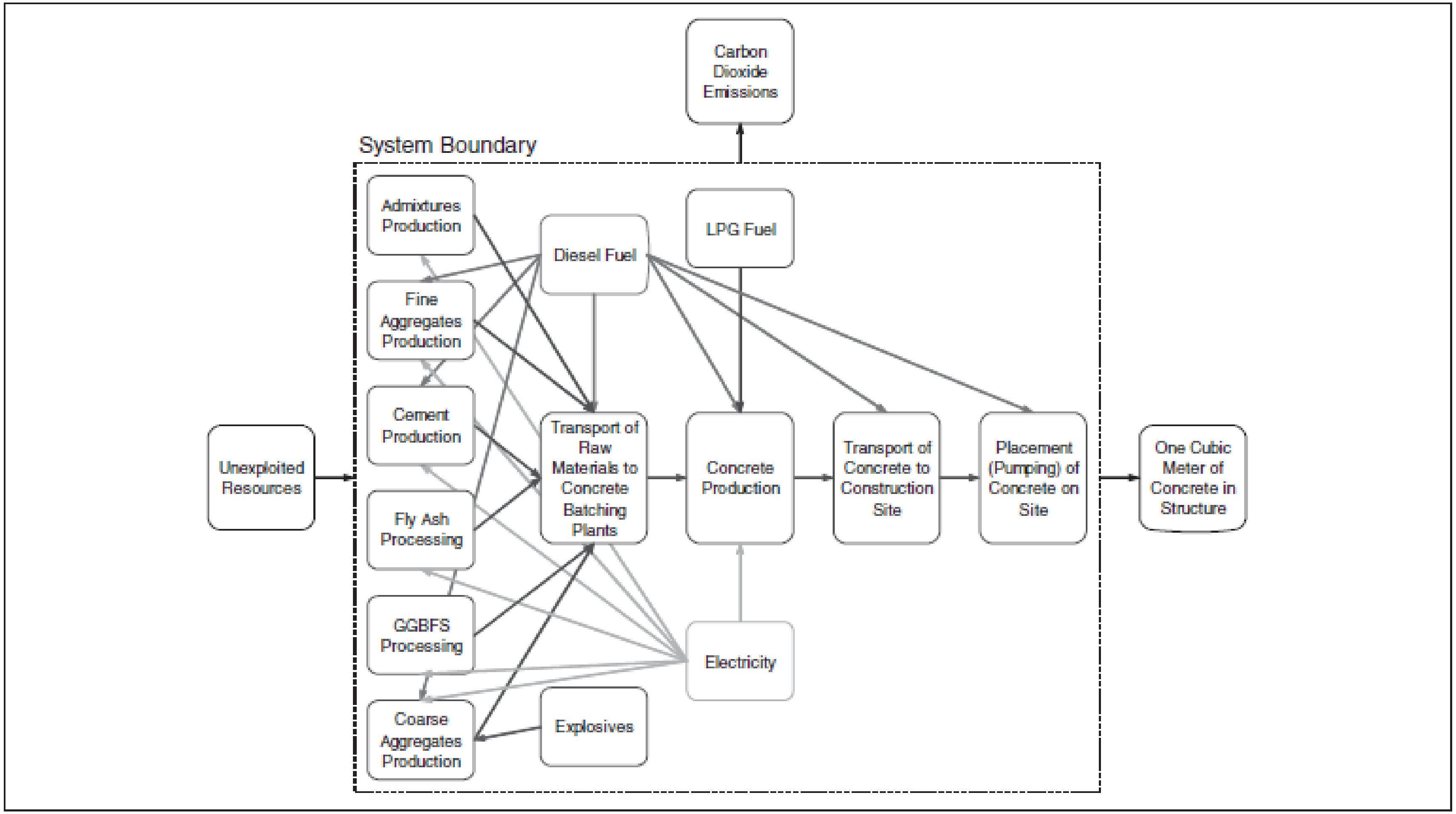


Figure 2.9 Concrete CO_2 emissions system diagram (Flower & Sanjayan, 2007)

The result of different quantity low-grade recycled aggregates add in to concrete mixture with mineral replacement on mechanical and environmental performance was studied by (Henry et al., 2011). They found that mixtures with low durability and low carbon impact provides the equilibrium state as by decreasing volume of raw material volume carries a tendency to lessen the water absorption. (Fantilli & Chiaia, 2013) in their research have studied the combination of mechanical behaviour and environmental aspect. They proposed new environmental-engineering performance index ratios with aspire to ascertain ecological-friendly concrete with satisfactory engineering performance. (McLellan, Williams, Lay, van Riessen, & Corder, 2011) carry out a recent research in examining the succession cost and carbon emission of the ordinary Portland cement (OPC) and geo-polymers in an Australian context. Results denote a large difference in the computed economical and environmental rate of geo-polymers. Results may be valuable or negative based on the supply location, energy and transportation. There is possible decrease from 44% to 64% for greenhouse gas emissions with fiscal expenses are 7% lesser to 39% higher with contrast to normal OPC.

Ideology for the advancement of less-carbon concrete are highlighted by (Proske et al., 2013). Based on their experimental results, they suggest three main ideas in developing low-carbon concrete which consist of the choice for cement with good class type and environmental-friendly minerals such as limestone, granulated blast-furnace slag (GBFS) or fly ash. Minimization of water proportion and minerals in the concrete mixture and optimization of the paste volume will resulting to a low-carbon concrete.

CHAPTER 3

RESEARCH METHODOLOGY

3.0 Introduction

This chapter will discuss the methods adopted in this study. The methods initially focus on preparing mix proportion, selecting available raw materials, material testing, and performance evaluation in fulfilling the objectives of the research. The effects of fly ash for different flowability of mortar will be examined through the mini slump flow test and mini V-funnel test.

The relationship of engineering properties performance will be determined from compressive strength tested at 3, 7, 14, 28 and 90 days. Simultaneously, water absorption test will be conducted at the age of cube 28 days. Environmental sustainability performance will be evaluated from the CO_2 footprint that resulted from the mix proportion and CO_2 emission inventory data (kg-CO_2/tonne). Performance index of the mixes evaluated from develop equation by (Fantilli & Chiaia, 2013) will be adopted. Ultimately, the relationship of cost factor to the engineering performance and environmental sustainability will be developed in order to obtain the optimum replacement of the mixes.

3.1 Mix Proportion

The mix proportion of the mortar mixes is shown in Table 3.1 and Table 3.2. Four different water/binder ratios (0.35, 0.40, 0.45 and 0.50), one control and four replacement levels of fly ash (10%, 20%, 40% and 60%) by weight of cement were adopted for this study. Superplasticizer dosage was determined earlier from the trial mixes to give three ranges of workability that is normal slump flow (targeted at ≤ 100 mm), high slump flow (targeted at 150 – 170 mm) and self-compacting flow (targeted at

240 – 260 mm). Sixty mortar mixes were prepared to determine the effect of superplasticizer dosage requirements for the flowability of mortar.

3.2 Materials

3.2.1 Ordinary Portland cement

Ordinary Portland cement used in this study is Tasek Cement conforming to ASTM Type I and labelled as CEM I.

3.2.2 Fine Aggregate

Manufactured silica sand was produced by a local mineral quarry and the sizes used were 8/16 (1.2 mm – 2.4 mm), 16/30 (0.6 mm – 1.2 mm), 30/60 (0.3 mm – 0.6 mm) and 50/100 (0.3 mm - 0.075 mm). A sieve analysis test was carried out prior to achieving the finess modulus of the silica sand used. Fineness modulus of 2.58 is obtained with a specific gravity of 2.64. Grading of silica sand are based to BS 882 : 1992 shown in Figure 3.1.

3.2.2.1 Sieve Analysis

The process of dividing a sample of aggregates into fractions of the same particle size is known as a sieve analysis, and its purpose is to determine the grading or size distribution of the aggregate. A sample of air-dried aggregate is graded by shaking or vibrating a nest of stacked sieves, with the largest sieve at the top, for a specified time so that the material retained on each sieve represents the fraction coarser than the sieve in question but finer than the sieve above (Neville and Brooks, 1997).

The grading of aggregates is important in order to get reasonable workability and furthermore producing economical concrete mixes. BS 882:1992 specifies the grading limits for fine aggregate as shown in Table 3.3. The former standard lays down overall limits and, in addition, specifies that not more than one in ten consecutive samples shall have a grading outside the limits for any one of the coarse, medium and fine grading labelled C, M and F, respectively.

Table 3.1 Mix proportion w/b 0.35 and 0.40

							SP Dos (%)		
Mixture	W/B	Water (kg/m³)	Cement (kg/m³)	Sand (kg/m³)	FA (kg/m³)	SP (kg/m³)	Normal	High	Self-Compacting
Mix 1A-C		192.5	550	1100	0	1.10	0.20	-	-
Mix 1B-C	0.35	192.5	550	1100	0	3.30	-	0.60	-
Mix 1C-C		192.5	550	1100	0	5.50	-	-	1.00
Mix 2A-10%FA		192.5	495	1100	55	0.99	0.20	-	-
Mix 2B-10%FA	0.35	192.5	495	1100	55	2.23	-	0.45	-
Mix 2C-10% FA		192.5	495	1100	55	3.47	-	-	0.70
Mix 3A-20% FA		192.5	440	1100	110	0.79	0.18	-	-
Mix 3B-20% FA	0.35	192.5	440	1100	110	1.54	-	0.35	-
Mix 3C-20%FA		192.5	440	1100	110	2.64	-	-	0.60
Mix 4A-40%FA		192.5	330	1100	220	0.53	0.16	-	
Mix 4B-40%FA	0.35	192.5	330	1100	220	0.99	-	0.30	-
Mix 4C-40%FA		192.5	330	1100	220	1.91	-	-	0.58
Mix5A-60%FA		192.5	220	1100	330	0.31	0.14	-	-
Mix 5B-60%FA	0.35	192.5	220	1100	330	0.62	-	0.28	-
Mix 5C-60%FA		192.5	220	1100	330	1.14	-	-	0.52
Mix 6A-C		180	450	900	0	0.90	0.20	-	-
Mix 6B-C	0.40	180	450	900	0	1.35	-	0.30	-
Mix 6C-C		180	450	900	0	2.48	-	-	0.55
Mix 7A-10%FA		180	405	900	45	0.73	0.18	-	-
Mix 7B-10%FA	0.40	180	405	900	45	1.13	-	0.28	-
Mix 7C-10% FA		180	405	900	45	2.03	-	-	0.5
Mix 8A-20% FA		180	360	900	90	0.61	0.17	-	-
Mix 8B-20% FA	0.40	180	360	900	90	0.97	-	0.27	-
Mix 8C-20%FA		180	360	900	90	1.76	-	-	0.49
Mix 9A-40%FA		180	270	900	180	0.43	0.16	-	-
Mix 9B-40%FA	0.40	180	270	900	180	0.68	-	0.25	-
Mix 9C-40%FA		180	270	900	180	1.27	-	-	0.47
Mix 10A-60%FA		180	180	900	270	0.23	0.13	-	-
Mix 10B-60%FA	0.40	180	180	900	270	0.31	-	0.17	-
Mix 10C-60%FA		180	180	900	270	0.72	-	-	0.40

Table 3.2 Mix proportion w/b 0.45 and 0.50

Mixture	W/B	Water (kg/m³)	Cement (kg/m³)	Sand (kg/m³)	FA (kg/m³)	SP (kg/m³)	SP Dos (%) Normal	High	Self-Compacting
Mix 11A-C		157.5	350	700	0	0.63	0.18	-	-
Mix 11B-C	0.45	157.5	350	700	0	1.09	-	0.31	-
Mix 11C-C		157.5	350	700	0	1.51	-	-	0.43
Mix 12A-10%FA		157.5	315	700	35	0.47	0.15	-	-
Mix 12B-10%FA	0.45	157.5	315	700	35	0.95	-	0.30	-
Mix 12C-10% FA		157.5	315	700	35	1.32	-	-	0.42
Mix 13A-20% FA		157.5	280	700	70	0.39	0.14	-	-
Mix 13B-20% FA	0.45	157.5	280	700	70	0.56	-	0.20	-
Mix 13C-20%FA		157.5	280	700	70	1.06	-	-	0.38
Mix 14A-40%FA		157.5	210	700	140	0.27	0.13	-	-
Mix 14B-40%FA	0.45	157.5	210	700	140	0.32	-	0.15	-
Mix 14C-40%FA		157.5	210	700	140	0.67	-	-	0.32
Mix 15A-60%FA		157.5	140	700	210	0.15	0.11	-	-
Mix 15B-60%FA	0.45	157.5	140	700	210	0.34	-	0.24	-
Mix 15C-60%FA		157.5	140	700	210	0.28	-	-	0.20
Mix 16A-C		125	250	500	0	0.38	0.15	-	-
Mix 16B-C	0.50	125	250	500	0	0.75	-	0.30	-
Mix 16C-C		125	250	500	0	1.00	-	-	0.4
Mix 17A-10%FA		125	250	500	25	0.33	0.13	-	-
Mix 17B-10%FA	0.50	125	250	500	25	0.68	-	0.27	-
Mix 17C-10% FA		125	250	500	25	0.95	-	-	0.38
Mix 18A-20% FA		125	250	500	50	0.30	0.12	-	-
Mix 18B-20% FA	0.50	125	250	500	50	0.60	-	0.24	-
Mix 18C-20%FA		125	250	500	50	0.88	-	-	0.35
Mix 19A-40%FA		125	250	500	100	0.25	0.10	-	-
Mix 19B-40%FA	0.50	125	250	500	100	0.45	-	0.18	-
Mix 19C-40%FA		125	250	500	100	0.80	-	-	0.32
Mix 20A-60%FA		125	250	500	150	0.20	0.08	-	-
Mix 20B-60%FA	0.50	125	250	500	150	0.38	-	0.15	-
Mix 20C-60%FA		125	250	500	150	0.70	-	-	0.28

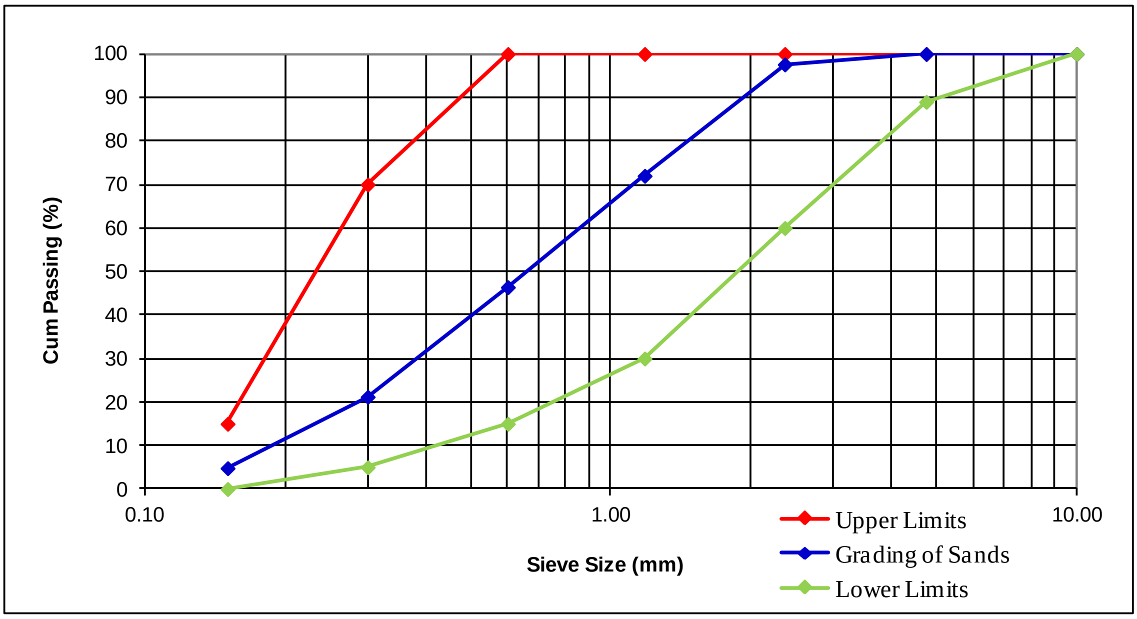


Figure 3.1 Particle size distribution of silica sand

Table 3.3 Grading requirement for fine aggregate (BS 882 : 1992)

Sieve size	Percentage by mass passing BS sieve			
	Overall limits	Additional limits for grading		
		C	M	F
10.00 mm	100	—	—	—
5.00 mm	89 to 100	—	—	—
2.36 mm	60 to 100	60 to 100	65 to 100	80 to 100
1.18 mm	30 to 100	30 to 90	45 to 100	70 to 100
600 µm	15 to 100	15 to 54	25 to 80	55 to 100
300 µm	5 to 70	5 to 40	5 to 48	5 to 70
150 µm	0 to 15[a]	—	—	—

NOTE Individual sands may comply with the requirements of more than one grading. Alternatively some sands may satisfy the overall limits but may not fall within any one of the additional limits C, M or F. In this case and where sands do not comply with Table 4 an agreed grading envelope may also be used provided that the supplier can satisfy the purchaser that such materials can produce concrete of the required quality.

[a] Increased to 20 % for crushed rock fines, except when they are used for heavy duty floors.

3.2.2.2 Fineness Modulus

Finess modulus is defined as the sum of the cumulative percentages retained on the sieves of the standard series, divided by 100. The standard series consists of sieves, each twice the size of the preceding one, viz.: 150 µm, 300 µm, and 600 µm, 1.18 mm, 2.36 mm, 5.00 mm and up to the largest sieve size present. The fineness modulus is frequently computed for fine aggregate compared to coarse aggregate. A usual value ranges from 2.30 to 3.0 is used with higher value of fineness modulus indicates that it is of coarser grading. Importance of the finess modulus calculation is to distinguished slight differences in sizes for the aggregates originate from same source. The slight variations may influence on workability of the fresh concrete (Neville and Brooks, 1997). The results of the sieve analysis and calculation of finess modulus are reported in Table 3.4

Table 3.4 Result of Sieve Analysis and Finess Modulus

Sieve Size (mm)	Mass Retained (g)	% Retained	Cum % Retained	Cum % Passing	**BS 882:1992. Table 4. Overall Limit**
10.00	0.00	0.00	0.00	100.00	100
4.75	0.00	0.00	0.00	100.00	89 to 100
2.36	12.00	2.40	2.40	97.60	60 to 100
1.18	128.00	25.60	28.00	72.00	30 to 100
0.600	128.00	25.60	53.60	46.40	15 to 100
0.300	126.00	25.20	78.80	21.20	5 to 70
0.150	82.00	16.40	95.20	4.80	0 to 15
Pan	24.00	4.80	-	-	
Total	500.00		258.0		

Finess Modulus Σ Cummulative % retained / 100 = 2.58/100 **= 2.58** (Equation 3.1)

3.2.3 Fly Ash

A Class F fly ash as mineral admixture used in this study is produced locally and supplied by TNB power station Kapar. Chemical compositions and physical properties of cement and fly ash from the XRF analysis test are as shown in Table 3.5 below.

Table 3.5 Chemical composition and physical properties

Component (%)	SiO	Al O	CaO	Fe O	MgO	SO	K O	TiO	CO	Specific gravity	Finess (m^2/kg)
Cement	18.47	4.27	64.09	2.06	2.08	4.25	0.28	0.11	4.2	3.11	390
Fly Ash	48.2	30.7	8.31	-	-	0.78	1.06	-	-	2.27	469

3.2.4 Water

Direct tap water was used. However prior to mixing, water was checked for any visible contaminants which will affect the hydration process.

3.2.5 Admixture

Chemical admixture used is a modified poly-carboxylate superplasticizer admixture “Sika 2055” with a specific gravity of 1.08.

3.3 Experimental Work

3.3.1 Mixing Procedure

The procedure in mixing the mortar mixture is based on standard practice as described by ASTM C305-12. By using standard mixer as described by ASTM C109/C 109M –01 as shown in Figure 3.2, the internal side of mixer was soaked with water to avoid absorption during mixing process. Fine aggregate, cement and mineral admixture was then added and were dry mixed for approximately 1½ minutes with low speed (140 ± 5 rotation/min). Then, three quarters of the total mixing water was put in, subsequently the liquid superplasticizer and finally the residual water. Wet mixing maintain with total period of five minutes. Machine was then stopped and the mortar allowed resting for 90 second. Throughout the first 15 second, mortar mixtures that cumulate on the side of the bowl was scraped down into the batch; for the remainder of this interval, the mixer enclosure was closed or the bowl covered with lid. In any case that requires a remixing interval any mortar adhering to the side of the bowl shall be quickly scraped down into the batch with the scraper prior to remixing.

Figure 3.2 Standard mini-mixer

3.3.2 Specimen Preparation

The test specimens were prepared by using a standard steel cube mould of 50 mm x 50 mm x 50 mm dimension as shown in Figure 3.3. Sixty mortar cubes were cast for each mortar mix that gives 1800 cubes of mortar specimens. Prior to casting, the cube mould was cleaned by using soft brush and a thin layer of mould applied to facilitate the removal of the cube mould upon the completion of casting. A mini slump flow test and mini V-funnel test were conducted to assess the workability of the fresh mortar. Specimens were then cast in the moulds and only the normal and high slump flow mixes were compacted, but self-compacting flow mixes were not subjected to any compaction. The mortar specimens were kept covered and cured in the moulds for 24 hours, after which they were removed from the moulds and placed in a curing tank at 20 – 21 ºC as specified by ASTM C511-09 as shown in Figure 3.4.

Figure 3.3 Cube mould (50 x 50 x 50) mm

Figure 3.4 Curing of specimens

3.4 Determination of Fresh Properties

3.4.1 Mini Slump Flow

The slump flow test for SCM is described in EFNARC 2002. It is designate to measure the parallel flow of SCC without any hindrance. Methods for the slump flow test and the commonly used slump test are almost identical. In conventional slump test, the difference in height between the cone and the spread concrete is quantify, whereas in the slump flow test the diameter of spread mixture is decided as the slump flow diameter. In this test, the truncated cone mould is placed on a smooth plate, filled with mortar, and lifted upwards as shown in Figure 3.5 and figure 3.6. The subsequent diameter of the mortars is measured in two perpendicular dimensions and the average is reported as the final diameter. Finally the relative slump is calculated by the following formula:

$$\Gamma_{p/m} = (d / d_0)^2 - 1 \quad \text{(Equation 3.2)}$$

$$\text{where, } d = \tfrac{1}{2}(d_1 + d_2) \quad \text{(Equation 3.3)}$$

And d_0 is the initial diameter of the cone, and d is the final diameter of flow.

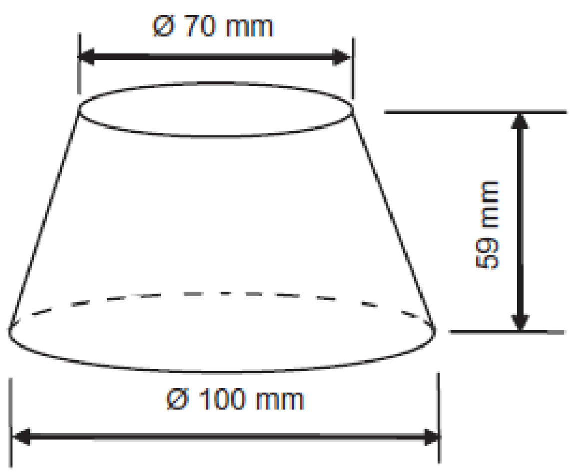


Figure 3.5 Internal dimensions of flow cone

Figure 3.6 Mini slump cone and tamping rod

Figure 3.7 Determination of high slump flow

3.4.2 Mini V-funnel flow

The mini V-funnel flow test for SCM is also described in EFNARC, 2002. The V-funnel is used to measure the flowability or viscosity of the SCC. The base opening is release to let the mortar mixes to flow once it has filled the funnel. The V-funnel time is the elapsed time (t) in second between the release of the base opening and the time when the light has noticeable from the base, while view from the top. The V-funnel test is also used to assess the fresh properties of SCM with a slight modification to the V-funnel apparatus as shown in Figure 3.8 and Figure 3.9.

The relative V-funnel speed is then calculated as:

$$R_m = 10/ t \qquad \text{(Equation 3.4)}$$

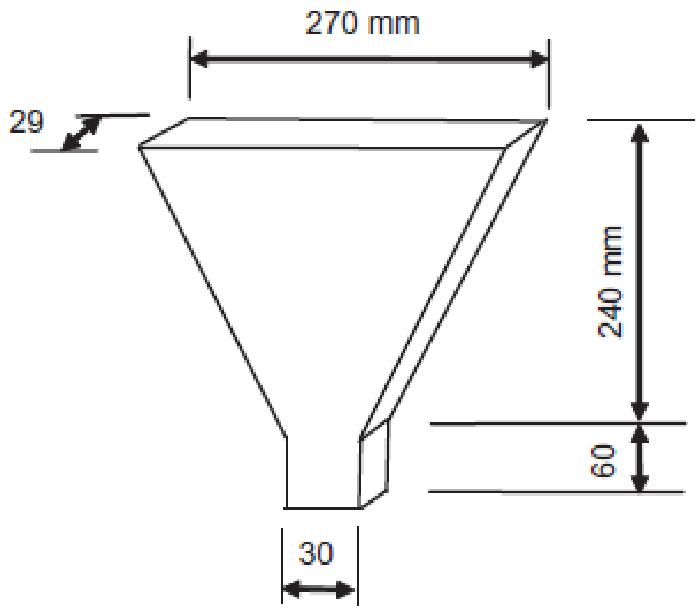


Figure 3.8 V-funnel to determine flow time of mortar

Figure 3.9 Determination of V-funnel time

3.5 Determination of Hardened Properties

3.5.1 Water Absorption

As an indicator for durability, a water absorption test as shown in Figure 3.10 was also conducted when the mortar cubes reached the age of 28 days. Water absorption was measured according to (BS 1881 : Part122, 2011).

3.5.1.1 Test Procedure

(i) Three samples were placed in the drying oven with temperature controlled at 105 ± 5 º C for 72 ± 2 hours.

(ii) During the drying process, further samples shall not be placed in the same oven and there shall be free access of air to all surfaces of the samples.

(iii) Cool each specimen for 24 ± 0.5 hours in a dry airtight vessel. Each of the specimen was weighed and immediately immersed in the tank containing clean water maintained at a temperature of 20 ± 1 ºC with its longitudinal axis horizontal and a depth in a way that there is 25 ± mm of water over the top of specimen. Designate this value as A.

(iv) Samples immersed in the water were left for 30 ± 0.5 minutes, and before weighing, the bulk of water and free water was removed from the surface by using cloth. Designate the final surface dry-mass after immersion as B.

(a) Mortar samples cooled in dry airtight vessel

(b) Mortar sample weighed

(c) Mortar samples immersed in the water for 30 ± 0.5 minutes

Figure 3.10 Determination of water absorption

3.5.1.2 Calculation for Water Absorption

The absorption of samples measured as enhancement in mass consequential from the submerging and presented as percentage of the mass of the dry samples.

$$\text{Absorption, } \% = [(B - A) / A] \times 100 \qquad \text{(Equation 3.5)}$$

where, A = mass of even-dried sample in air, g

B = mass of fly ash-dry sample in air after immersion, g

3.5.2 Compressive Strength

The compressive loading tests Figure 3.11 on specimens of mortar were carried out on a compression testing machine of capacity 500 kN with the loading rate of 0.9 kN/s. The specimen used was 50 mm cube. The test was performed according to (ASTM C109, 2011) at 3, 7, 14, 28 and 90 Days. The specimens were tested immediately after taking the cubes from the curing tank in wet condition.

Figure 3.11 Determination of compressive strength

3.5.2.1 Test Procedure

Subsequent of curing in water for 24 hours, samples shall be taken for testing instantly during dry surface condition. Any presence of moisture and gravel shall be clean off. The dimension of the samples recorded to the nearest 0.2 mm and their weight are taken before testing.

As the specimen was placed in the strength machine, the tested surface of the machine shall be clean off and any presences of other materials are then get rid from the surface. The samples are to be noted in contact with the compression platens. The cubes samples shall be positioned in such a condition that the load shall be affect to the cast surface of the cubes, instead of the top and bottom.

Prior to the running of the machine, the indication on the machine such as sizes of cubes, number of cubes loading rate should be keyed in carefully. The highest load affect to the samples shall be marked and the exterior of the samples for any irregular appearance on the mode of failure should be recorded.

3.5.2.2 Calculation of Compressive Strength

The obtained compressive strength is calculated by dividing maximum load pertaining to the samples over the cross sectional area. It is determine from the mean dimensions of the section and shall be expressed to the nearest N/mm^2. The mean of three values shall be taken as the representative of the batch provided that the standard deviation not more than ± 3%. Otherwise additional specimens will be tested.

3.6 Environmental Sustainability Performances

Table 3.6 shows CO_2 emission inventory data (kg-CO_2/tonne) which represent the embedded CO_2 values from cradle to grave of each element material of concrete production. Environmental sustainability performance was evaluated based on the CO_2 footprint of each of the mortar mixture. CO_2 footprint was derived from mortar mix proportions (kg/m^3) shown in Table 3.1 and Table 3.2 and the CO_2 emissions of concrete constituent in Malaysia (kg-CO_2/tonne) as shown in Table 3.6 below. Multiplication method was adopted in calculation of CO_2 footprints by using data from the mix proportion and CO_2 emission.

Table 3.6 CO_2 emissions of concrete constituent in Malaysia (Soo, 2011)

Element	Specific Emission (kg-CO /tonne)
Aggregate	4
Cement CEM I	1000
Fly Ash	50
Water	0.3
Admixtures	0.2

3.7 Performance Index

In order to evaluate the level of engineering properties, a performance index was suggested to relate the engineering properties i.e. compressive strength and durability and environmental sustainability properties. Few researchers adopt index in their research in order to carry out some kind of evaluation on their engineering performance. An index described as integer or sign, presents in a subscript or superscript for numerical equations that designate a process to be executed. An index is also number obtained from formula that employs to distinguish set of data. (Fantilli & Chiaia, 2013) which introduces the environmental-mechanical indicators in order to cater to ecological-friendly concrete with satisfactory engineering properties. They observe that the environmental performances of concrete structures have largely been investigated, conversely engineering performances and environmental feature often ignored by researchers. They propose on some ecological-mechanical fraction, in which the CO_2

released (environmental aspect) corresponds to be the numerator, while the mechanical properties represent the denominator as indicated in the equation below:

$$I = \frac{CO \quad Released}{Mechanical\ Properties} \qquad \text{(Equation 3.6)}$$

The excellent ecological-engineering performances are achieved when the index, is the lowest (Fantilli & Chiaia, 2013). (Kayali & Sharfuddin Ahmed, 2013) suggest a similar approach in their research by proposing a concept of performance index in assessing high volume replacement fly ash concrete. They addressed that relatively by adapting qualitative conditions to depict the engineering properties; as an alternative, a quantitative assessment may be allocated.

The performance index for strength and durability to the environmental sustainability was compared through their relative performance index with considering their mechanical and durability property performance as 1.0, which demonstrate its performance is comparatively lesser to OPC control or more than 1.0. This brought to attention whether the particulare mixes shows improvement result or vice versa than opc mortar.

Example as shown below for normal mixes, w/b ratio 0.35

Control mixes; I = CO_2 released / Mechanical properties (Equation 3.7)

$$= \frac{554.46 \text{ kg-}CO_{2/m}{}^3}{62.95 \text{ MPa}}$$

$$= 8.808 \text{ kg-}CO_{2/m}{}^3 / \text{MPa}$$

10% Fly ash mixes; I = CO_2 released / Mechanical properties (Equation 3.8)

$$= \frac{502.21 \text{ kg-}CO_{2/m}{}^3}{70.13 \text{ MPa}}$$

$$= 7.161 \text{ kg-}CO_{2/m}{}^3 / \text{MPa}$$

$$\text{Relative performance index, } I_{relative} = \frac{I_{10\%FA}}{I_{Control}} \qquad \text{(Equation 3.9)}$$

$$= \frac{7.161 \text{ kg-CO}_{2/m}{}^{3} \text{ / MPa}}{8.808 \text{ kg-CO}_{2/m}{}^{3} \text{ / MPa}}$$

$$= \underline{\underline{0.81}}$$

The performance of fly ash concrete may possibly remark as value less than 1.0, which defining the performance is comparatively lower to OPC mortar, or may expressed as value more than 1.0 by anticipating the performance of OPC mortar as 1.0 for any mechanical and durability properties. These brought to attention that the mortar is performing better than OPC mortar in relation to the particular performance.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

This chapter presents the overall findings on the effects of fly ash on the properties of fresh and hardened mortar for three different flowabilities. The investigation examines fresh properties of slump flow test (Γ_m) and V-funnel test (R_m). Hardened mortar specimens were tested at different ages of 3, 7, 14, 28 and 90 days to determine its compressive strength and water absorption. The environmental sustainability performance evaluation based on the results of CO_2 footprint calculation will also be elaborated in this chapter.

4.1 Engineering Performances

The fresh properties tests were carried out through mini-slump flow test and mini V-funnel test which indicate the workability of the mixes. On the other hand, the water absorption test helps to predict the durability properties of the mortar mixes. The fresh tests act as a measure of workability, while water absorption assumes the role as a durability indicator and compressive strength as the strength.

4.1.2 Workability Assessment

4.1.2.1 Mini Slump Flow

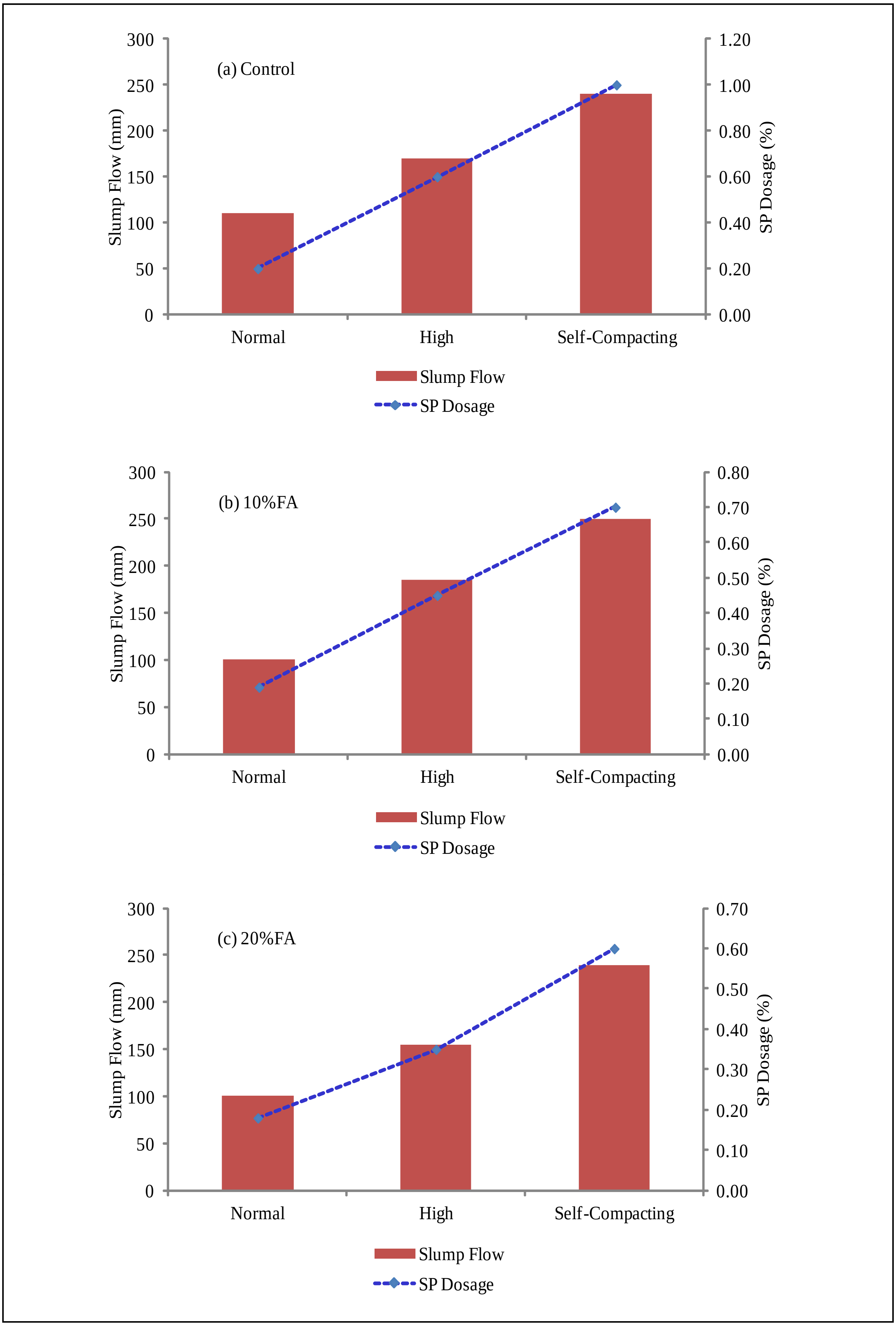
Mini slump flow test was carried out to achieve three different ranges of slump characteristics. They are normal flow (targeted at slump flow diameter of 100-120 mm), high flow (targeted at slump flow diameter 150 – 170 mm) and self-compacting flow (targeted at slump flow diameter 240– 260 mm). The superplasticizer dosage was altered during the trial mix stage to obtain slump flow diameter within the chosen range.

SCM mixes were specifically designed by changing SP dosage to satisfy the requirements stipulated by EFNARC, (2002). Figure 4.1 shows the effect of superplasticizer dosage on the slump flow. The flowability of the mixes generally improves specifically in self-compacting mixes with the incorporation of fly ash. This could be due to the physical characteristics of fly ash itself which is round and spherical in shape. These properties allows for better rolling capability and helps to elevate the lubrication between particles.

The fineness of powder materials such as fly ash is widely used to improve the workability of the mixes and reduce the bleeding effects. It should also be noted that fly ash provides cohesiveness and plasticity of a mortar. SP dosage is playing its role as dependent variable in order to achieve targeted workability which is normal, high and self-compacting flow. Hence, it can be concluded that the SP dosage utilized is highly dependent on the percentage of fly ash replacement level and workability. By increasing the fly ash replacement level, it will result in a better workability especially for normal mixes. It was observed from Figure 4.1 that increasing the fly ash level enhanced the workability although a lower SP dosage was required to achieve the targeted slump. These findings are similar with previous study by (Paya, 1995; Sua-iam & Makul, 2014), and (Berndt, 2009) which reported that fly ash gave the most significant improvement in workability. (Şahmaran, Yaman, & Tokyay, 2009) addressed that by using high volume of fly ash in SCC not only will improve workability and transport properties but also made it possible to achieve better compressive strength.

For control mixes without any replacement of fly ash, the highest SP dosage was recorded at 1.0% to give self-compactability spread flow at 240 mm as shown in Figure 4.1. Meanwhile, during the maximum level of fly ash replacement, 60% gives the lowest SP dosage at 0.14%, 0.28% and 0.56% to give normal spread flow at 100 mm, high flow spread at 155 mm and self-compacting spread flow at 255 mm respectively. The increase in SP dosage is due to the combined effect of greater paste volume and reduced fine material content which decreased the resistance of flowing ability of the mortar. A similar trend line is noticed for w/b ratio of 0.40, 0.45 and 0.50 as indicated in Appendix A. to Appendix C where high dosage of SP was required for control mixes to achieve normal spread flow, high spread flow and self-compactability spread flow. However, for 60% fly ash replacement, the SP dosage needed to be reduced significantly. This finding was similar to Khaleel and Abdul Razak (2012) study where for every mixes irrespective of w/b ratio, elevating fly ash substitution level gave a rise in volume of fly ash in paste. This resulted in lower mortar density as the fly ash density of 2.27 is much lower compared to that of cement.

It is clear that there is a good relationship between slump flow and SP dosage whereby increasing SP dosage leads to greater flowability. The resistance of the fresh mortar phase to flow decreases due to the liquefying action and consequently increases the flow spread of mortar. It is also observed from the overall results that w/b ratio plays a vital role in affecting the flow spread. Increment in w/b ratio was found to lower the paste volume and contain greater fine material which produced a much lower flow spread.



(a) Control
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage
(b) 10%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage
(c) 20%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage

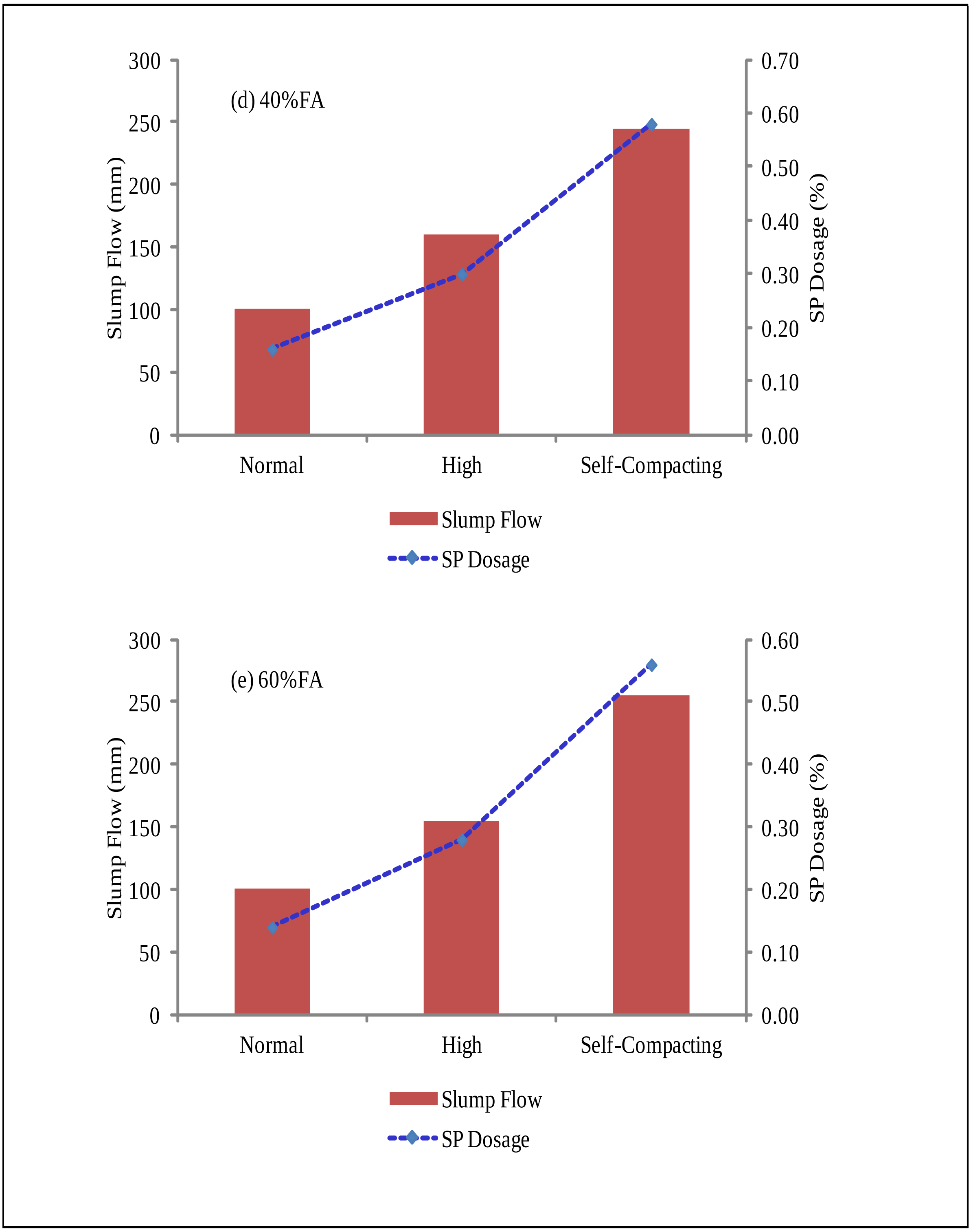


Figure 4.1 Slump flow – SP dosage at w/b 0.35

4.1.2.2 Relative SP Dosage

Relative SP dosage plot is defined as ratio of the SP dosage to the control mixture. Figure 4.2 to Figure 4.5 depict the relative performance of mortar mixes at various SP dosages. The figures illustrate linear trends for all mixes at each replacement level of fly ash. Comparing the relative performance of mixes with respect to SP dosage, better performance was observed at lower w/b ratio. It was found that for normal flow mix with the increase of fly ash from 10% to 20%, 5% drop of the relative SP dosage occurred. Similarly, 10% reduction of SP demand was recorded between 20% to 40% fly ash and 40% to 60% fly ash. High flow mix recorded large variation with 17% of SP reduction while added fly ash from 10% to 20%. Eventually, self-compacting flow mix gave a reduction of 10% with addition of 10% to 20% fly ash. This condition may be due to addition of fly ash resulted in a roller bearing effect which increased with the volume of fly ash added. Moreover, fineness of fly ash creates a lubricating effect within the mixes.

There is a noticeable difference in the pattern of flow for all three types of mixes. The variation for normal flow to high and self-compacting was much larger compared to high and self-compacting. Addition of fly ash from 40% to 60% was found giving large variation at normal flow mix with 11% of SP reduction. However, at high flow mix SP reduction of 6% was recorded and this was similar for every percentage fly ash replacement. Self-compacting flow shows a large variation at 40% to 60% replacement of fly ash with 19% SP reduction was recorded.

Comparing relative SP dosage at w/b 0.40 as shown in Figure 4.3, again similar linear trends were observed as before. Small variation was observed throughout every type of flow mixes at each replacement level. It was found that at normal flow mix, a 5% SP reduction was recorded with addition of 10% to 20% and 20% to 40% fly ash.

However, a large variation was observed at 40% to 60% fly ash which recorded 15% of SP reduction. Similarly, addition of fly ash at 40% to 60% at high and self-compacting flow gave a large variation which recorded 27% and 13% respectively. It can be concluded generally that reduction in relative SP dosage at each replacement level produces a proportionate decrease in SP demand.

Figure 4.4 illustrates a linear trend line for w/b ratio as obtained before for other ratios. Self-compacting flow produces much higher relative flow spread followed by high and normal flow. A proportionate reduction was observed for every flow types at 10%, 20% and 40% of fly ash replacement. However, a sudden drop in relative SP was noticed at 60% fly ash of self-compacting flow. This may due to the fact that increase in fly ash replacement at higher w/b ratio requires much lesser SP dosage. A large variation was also observed for the high flow to normal flow mixes. Addition of fly ash from 40% to 60% was found giving large variation at normal flow mix with 11% of SP reduction. However, at high flow mix SP reduction of 6% was recorded and this was similar for every percentage fly ash replacement. Self-compacting flow shows a large variation at 40% to 60% replacement of fly ash with 19% SP reduction was recorded.

Relative SP dosage at w/b ratio 0.50 is illustrated in Figure 4.5. A similar linear trend as w/b 0.35, 0.40 and 0.50 was observed. It was observed that for normal flow mix, reduction of SP at 20% to 40% and 40% to 60% was recorded at 13%. This value is 6% more than addition of 10% to 20% fly ash. In addition, high flow mix recorded a reduction of 10% for 10% to 20% fly ash and 40% to 60% fly ash. Addition of fly ash from 20% to 40% recorded 20% of SP reduction. Self-compacting flow mix recorded 10% of SP reduction at 40% to 60% fly ash. Similarly, at 10% to 20% and from 20% to 40% recorded 8% of SP reduction.

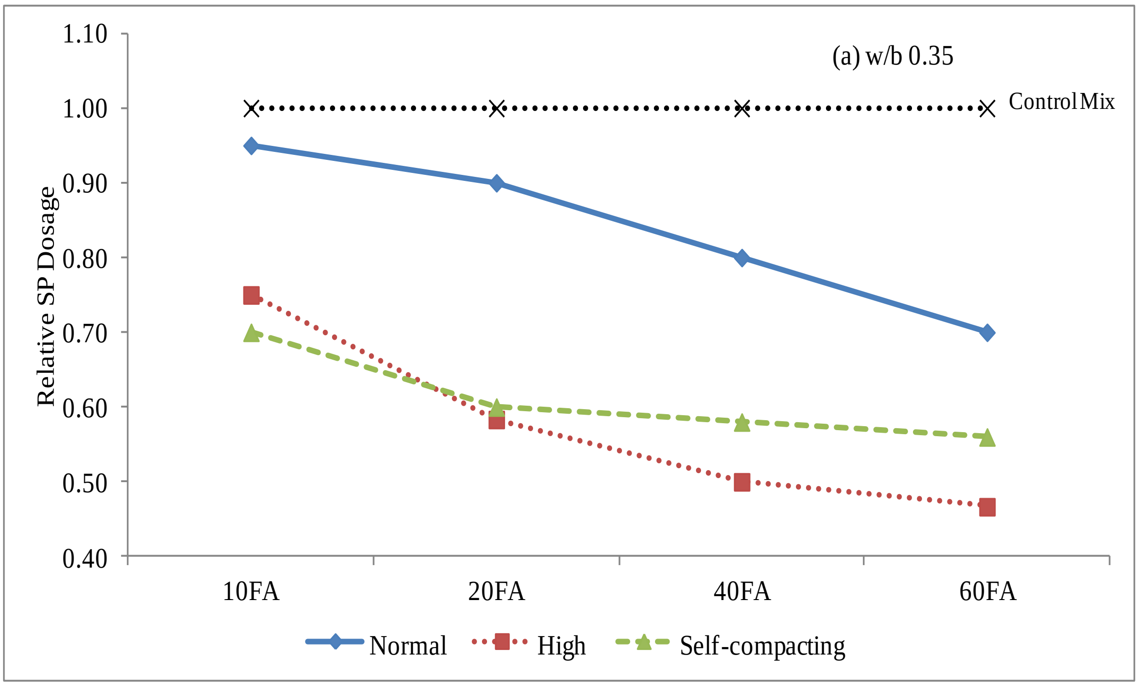


Figure 4.2 Relative SP dosage at w/b 0.35

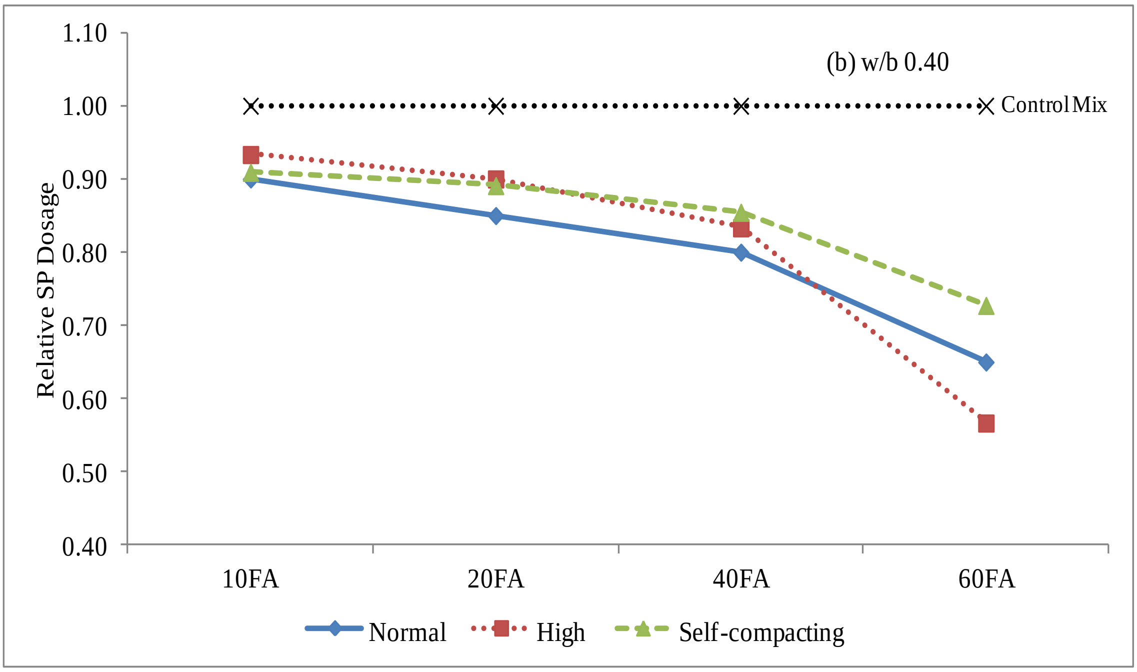


Figure 4.3 Relative SP dosage at w/b 0.40

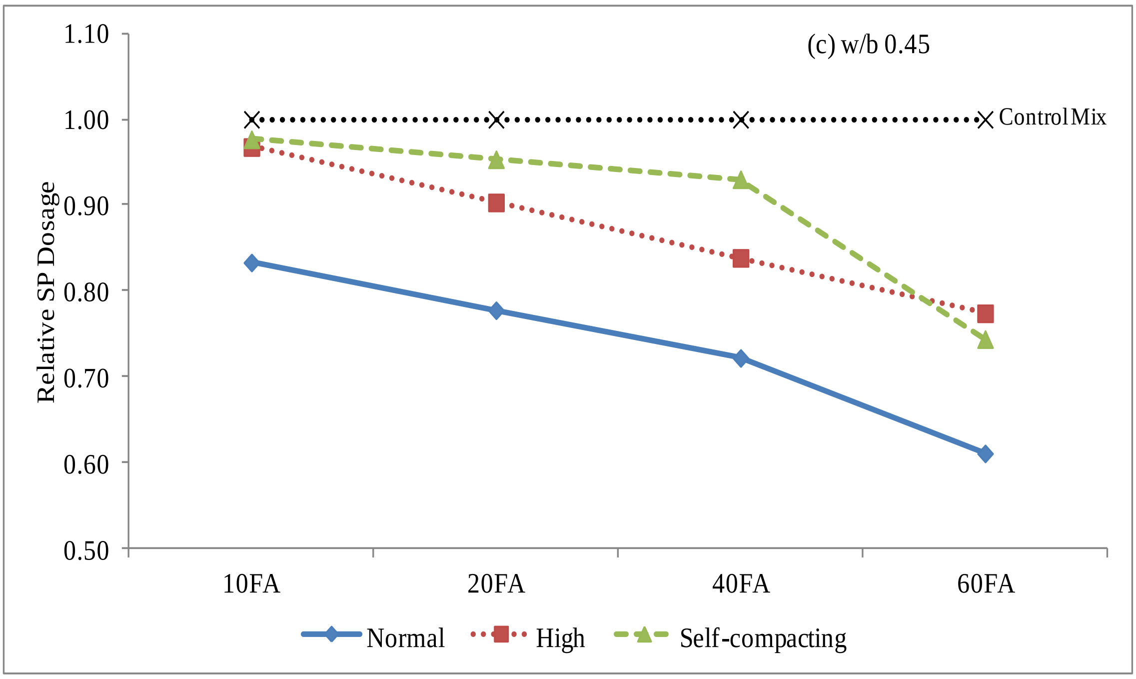


Figure 4.4 Relative SP dosage at w/b 0.45

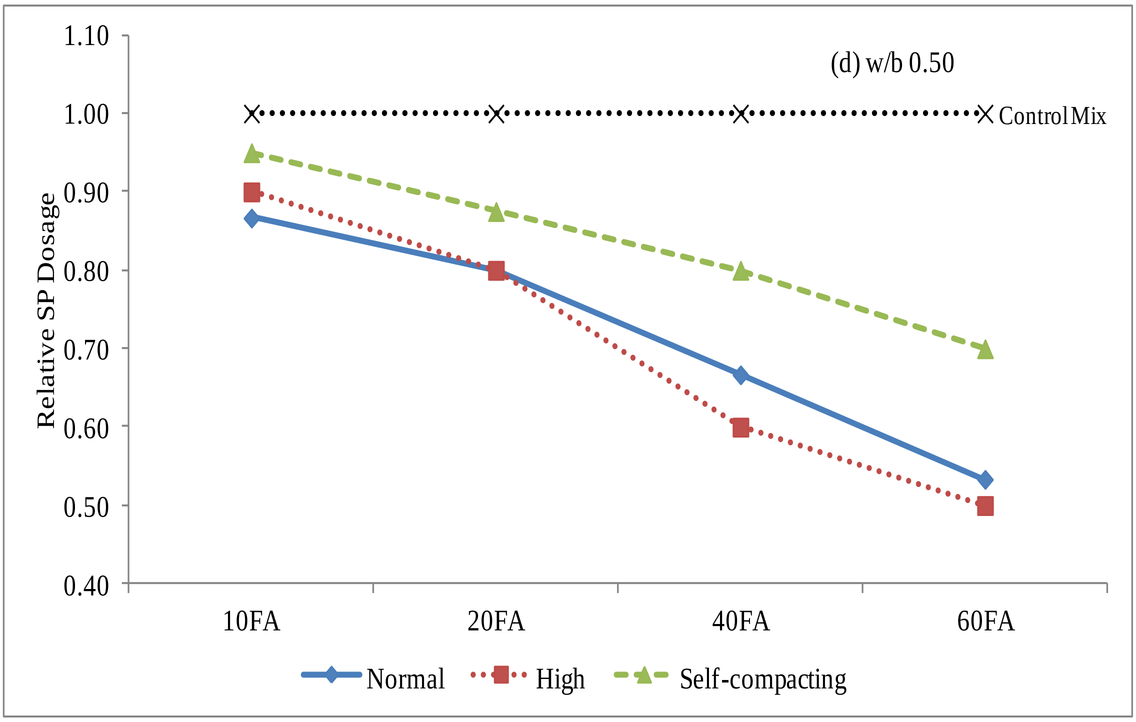


Figure 4.5 Relative SP dosage at w/b 0.50

4.1.2.3 Mini V-Funnel Flow

EFNARC, (2002) has specified that the V-funnel test is carried out in order to assess the viscosity and filling ability of self-compacting concrete. V-funnel testing is designed specifically for self-compacting mixes. Figures 4.6 to Figure 4.9 represents the relationship between SP dosage and V-funnel time for w/b 0.35, 0.40, 0.45 and 0.50 and the result shows a similar linear trend. The reduction of SP dosage and V-funnel time observed gave similar results throughout all w/b ratios. It is clearly seen from the entire Figures that at control with high percentage of SP dosage, higher V-funnel time was achieved in order to give the required flow spread of self-compacting mixes from 240 mm to 260 mm. At every w/b, results show that by decreasing the SP dosage reduced the time required for the mixes to completely flow from the mini V-funnel.

It was observed that with the addition of fly ash at every replacement levels 10%, 20%, 40% and 60% respectively, a proportionate reduction with the V-funnel time occurred. It is also observed that control indicates higher SP dosage thus giving higher V-funnel time. The apparent reason of this is due to the liquefying and dispersing actions of the SP which allowed decrease in the flow resistance. Control mixes at lower w/b ratio also indicated a large variation of V-funnel time to SP dosage plots. However, a small variation was observed at a higher w/b ratio. The mix proportions indicates that binder proportions are low with less water added into the mixes which can be attributed to less SP present in the mixes. Thus leading to a less time required for the mixes to completely fill the V-funnel.

It can be seen that the addition of fly ash up to maximum level has a significant effects on the mini V-funnel time. For instance, at a lower w/b ratio of 0.35, the addition of fly ash from 10%, 20%, 40%, and 60% increased the V-funnel time at a gradually increasing ratio 5%, 15%, 20% and 24%. This observed phenomenon was expected, as an increase in fly-ash should always improve the flowability of mortar. It is noteworthy that for control mixes (without any addition of fly ash) the V-funnel time is higher due to the lack of excess water to provide lubrication.

Figure 4.10 shows the relationship between the relative slump flow (Γ_m) and the relative funnel time speed (R_m). The figure clearly indicates that results obtained is within the limits set by EFNARC (2002), which states that for relative slump flow, (Γ_m) = 4.8 and for relative funnel time speed, (R_m) is set at 1.2. However, some data falls on the borderline limits which mostly occurred at 60% fly ash at much higher w/b ratios of 0.45 and 0.5 respectively. Şahmaran et al. (2006) reported similar trend of results for relative slump flow to relative V-funnel speed.

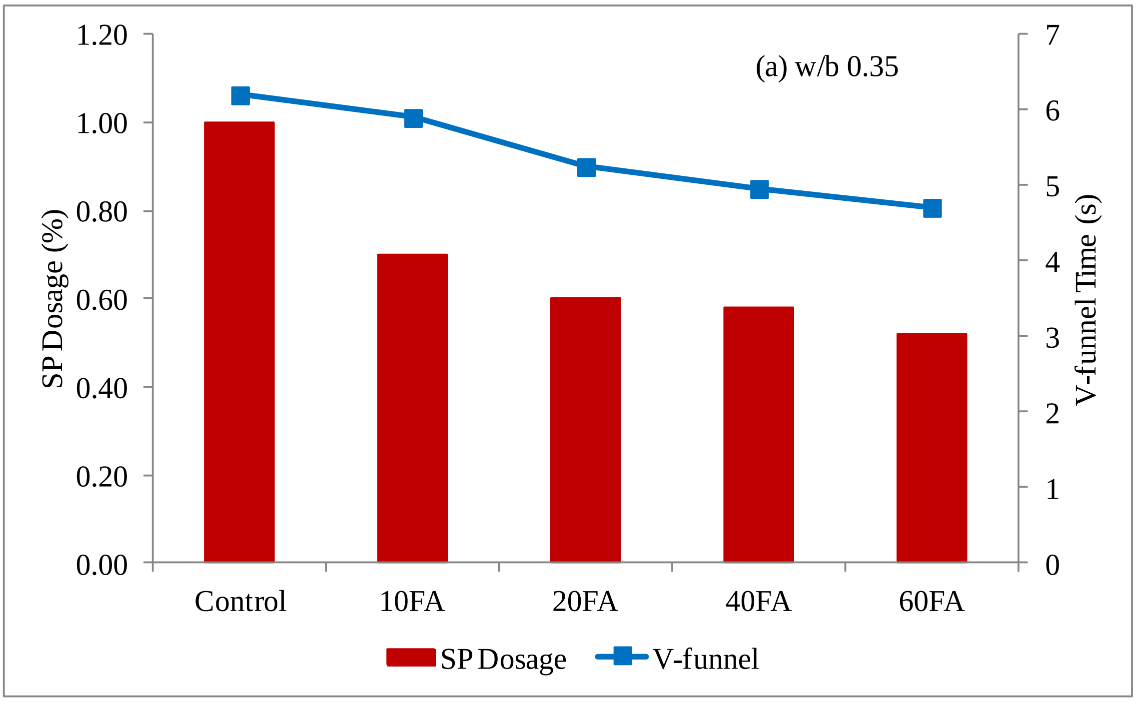


Figure 4.6 V-funnel time – SP dosage at w/b 0.35

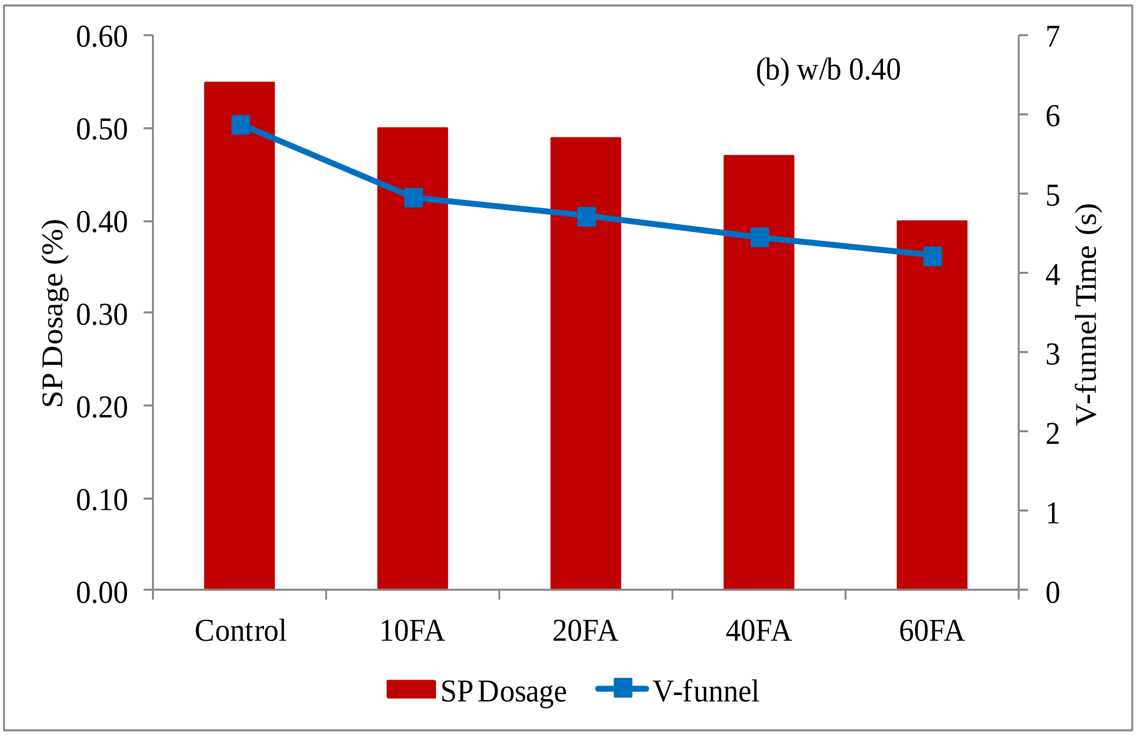


Figure 4.7 V-funnel time – SP dosage at w/b 0.40

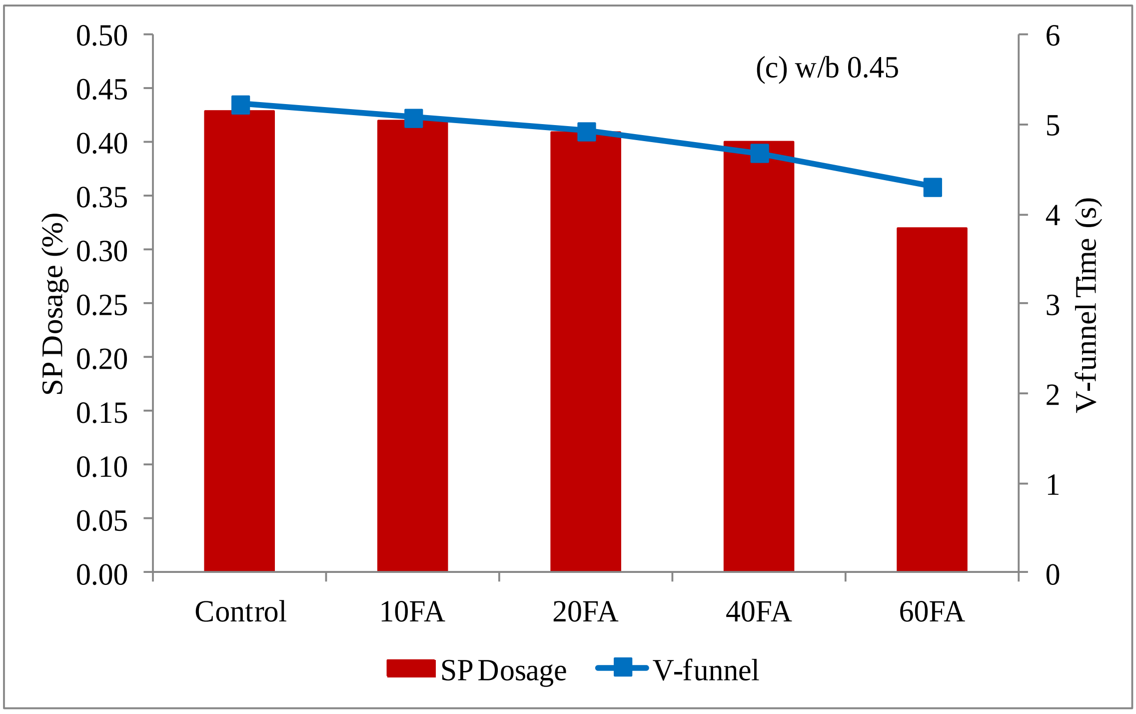


Figure 4.8 V-funnel time – SP dosage at w/b 0.45

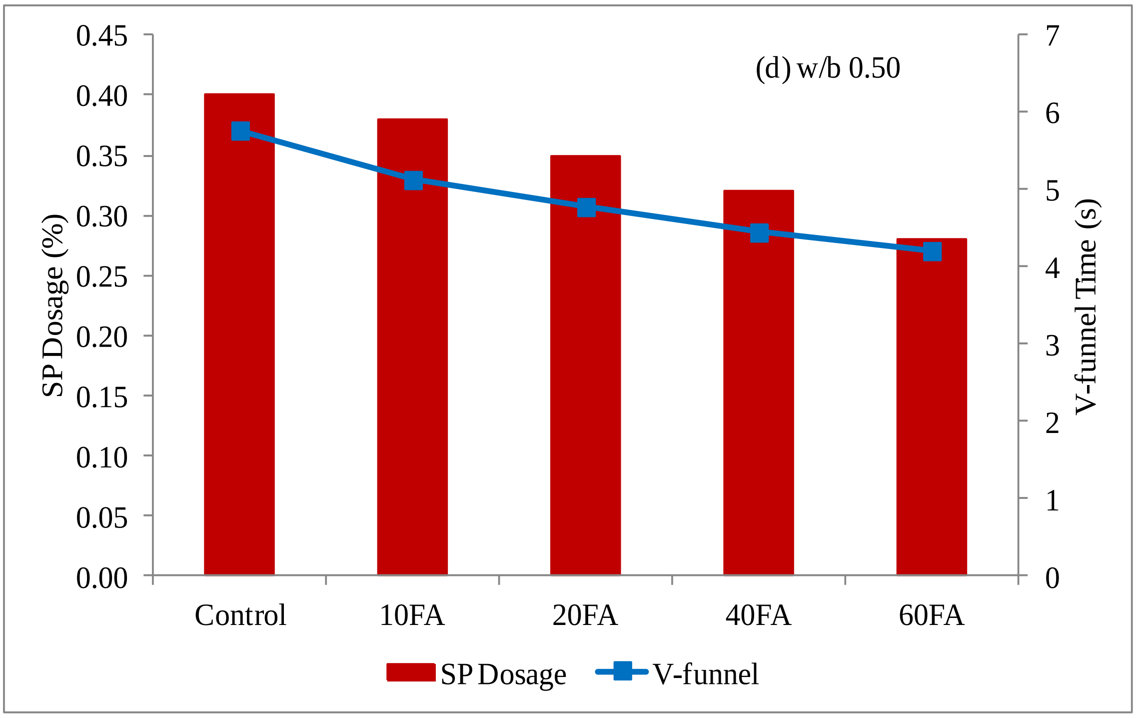


Figure 4.9 V-funnel time – SP dosage at w/b 0.50

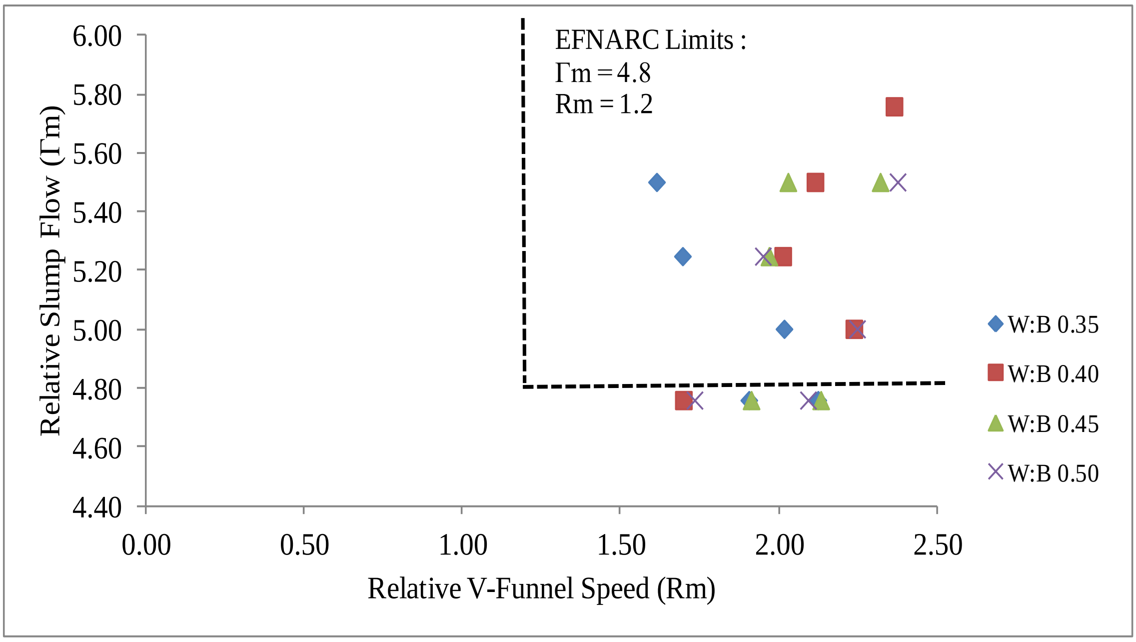


Figure 4.10 Relative slump flows – relative V-funnel speed

4.1.3 Hardened Properties

Hardened properties of mortar specimens were assessed through water absorption test when the age of mortar reached 28 day and compressive strength obtained at 3, 7, 14, 28 and 90 days.

4.1.3.1 Water Absorption

Concrete with a good design and sound construction, presents excellent durability and will extend the service time of any structure. Concrete structures that were constructed a hundred years ago still exist today. The expanded service life resulting from reducing the consumption of energy in a new building and infrastructure will also reduce the maintenance schedule and effects on the limited sources. The first line of defence against deterioration is good quality, and to ensure the concrete is impermeable. Good quality in material selection, mix ratio and excellent construction planning is necessary to ensure durable concrete. Ensuring the integrity and durability of concrete is essential in order to utilize the equity already in the existing structure and avoid the need to re-invest in materials and energy sooner than is necessary (Cement & Concrete Institute, 2011).

As a durability indicator, the water absorption test was carried out when the mortar specimens had reached 28 days. The water absorption test was carried out in accordance with BS 1881: Part 122, 1983. Figure 4.11 to Figure 4.14 below show the results of water absorption for normal, high and self-compacting flow based on their respective w/b ratios of 0.35, 0.40, 0.45 and 0.50. From the figures, it shows that there was an identical trend for each w/b ratio. The control for all w/b ratios for normal flow mortar gave the highest water absorption. Meanwhile, the 60% replacement level of fly ash for all w/b ratios was observed to give the lowest water absorption.

Figure 4.11 depicts the water absorption of the mortar specimens for the w/b ratio of 0.35. Compared to the control, the mixes with the replacement of Portland cement with 10%, 20%, 40% and 60% fly ash showed lower water absorption properties. This situation was similar to those obtained for the high flowable and SCM mixes. Generally, the addition of fly ash appeared to decrease the water absorption and elevate the durability performance of the mortar samples. It appears that the water transportation for all the mortar samples is affected by two factors – the pores of the cement paste and the interfacial transition zone (ITZ) between the cement paste and the aggregate (Kim, Jeon, & Lee, 2012). It is noted that the volume of water absorption in the mortar specimens corresponds with the degree of porosity. The porosity of mortar with the addition of fly ash aggregate was higher than that of the mortar without fly ash. The proportion of aggregate in the mixture was designed to decrease as the w/b ratio decreased, as presented in the mix proportion in Table 3.1 and Table 3.2. Therefore, the absolute value of the porosity in the specimens would decrease along with the w/b ratio.

Figure 4.12 shows the water absorption performance of the mortar samples for the 0.40 w/b ratio. A similar trend of results was observed when compared to the 0.35 w/b mixes. Increasing the fly ash replacement level was found to decrease the water absorption. The results were consistent at every substitution level, which may be due to the inferior value of the specific gravity for fly ash. In addition, the highly porous nature of fly ash may have contributed to this situation. The porosity of the mortar samples with the addition of fly ash is lower than for those without the fly ash (control), which resulted in high absorption for the control.

Parallel trends were observed for the w/b ratios 0.45 and 0.50, as illustrated in Figure 4.13 and Figure 4.14, in that the control for all mixes showed that the high absorption decreased when replaced with fly ash. From the Figures, it can be deduced that although the water absorption ranges for normal and high are similar regardless of the w/b ratio, the water absorption ranges for self-compacting mixes showed a decrease for w/b ratios 0.35, 0.40 and 0.45. The trends for the water absorption ranges are tabulated in Table 4.1 below. The self-compacting was observed to have a low range of 1.5% < WA < 2.5% of absorption compared to the other w/b ratios. This showed that the self-compacting mix at a lower w/b ratio is more durable compared to the high w/b ratio. Similar findings were reported by (Siddique, 2013) in that all the SCC mixes had low absorption (less than 10%). (Dinakar, Babu, & Santhanam, 2008) reported that self-compacting mix with addition of high volume fly ash have highly permeable voids. This may due to the fact that increase in fly ash replacement at higher w/b ratio requires much lesser SP dosage.

Table 4.1 Ranges of water absorption for all w/b ratio

	w/b 0.35	w/b 0.40	w/b 0.45	w/b 0.50
Normal	2 % < WA < 3 %	2.5 % < WA < 3.5 %	3 % < WA < 4 %	3 % < WA < 4 %
High	2 % < WA < 3 %	2.5 % < WA < 3.5 %	3 % < WA < 4 %	3 % < WA < 4 %
Self-compacting	1.5 % < WA < 2.5 %	2 % < WA < 3.5 %	2.5 % < WA < 3.5 %	3 % < WA < 4 %

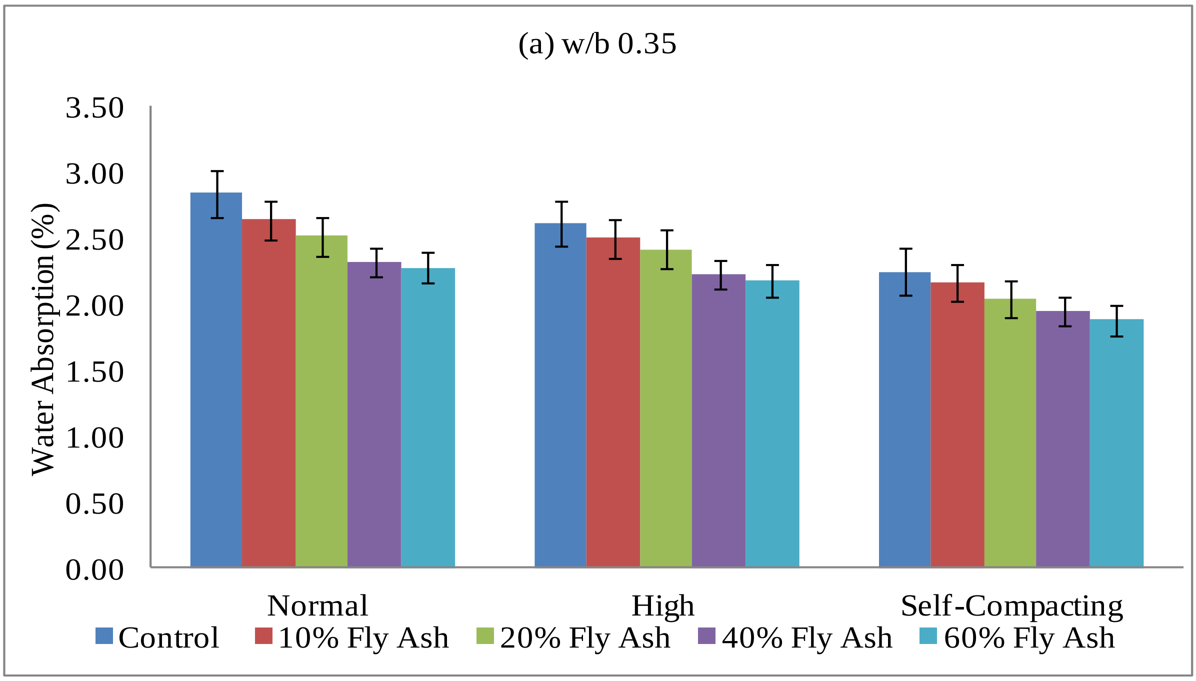


Figure 4.11 Water absorption at w/b 0.35

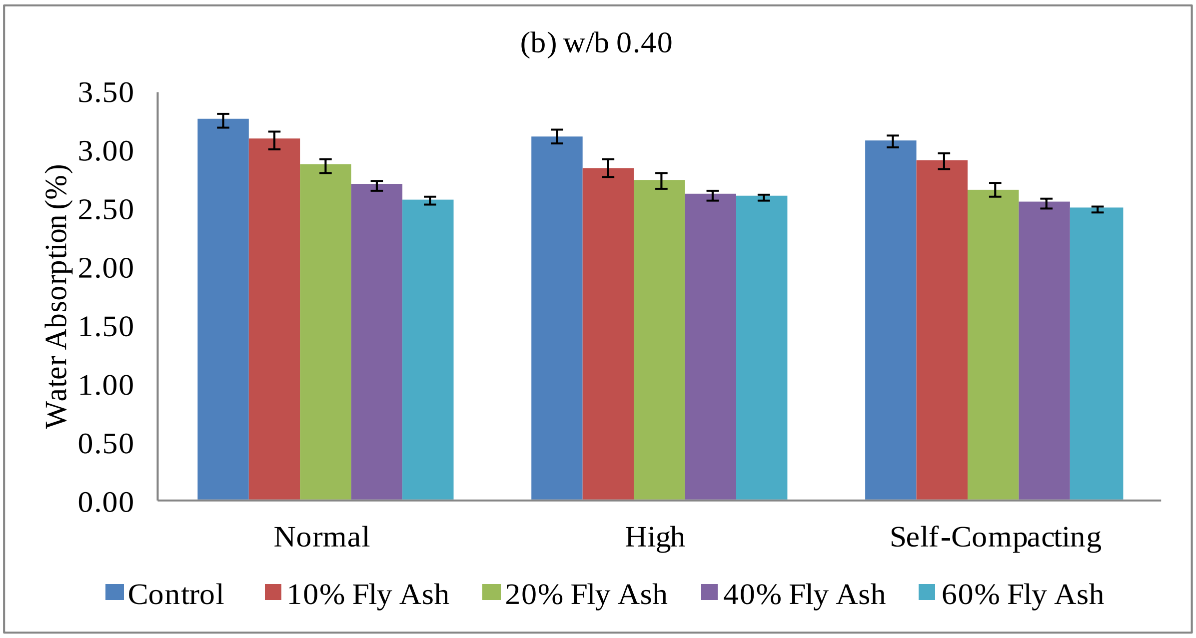


Figure 4.12 Water absorption at w/b 0.40

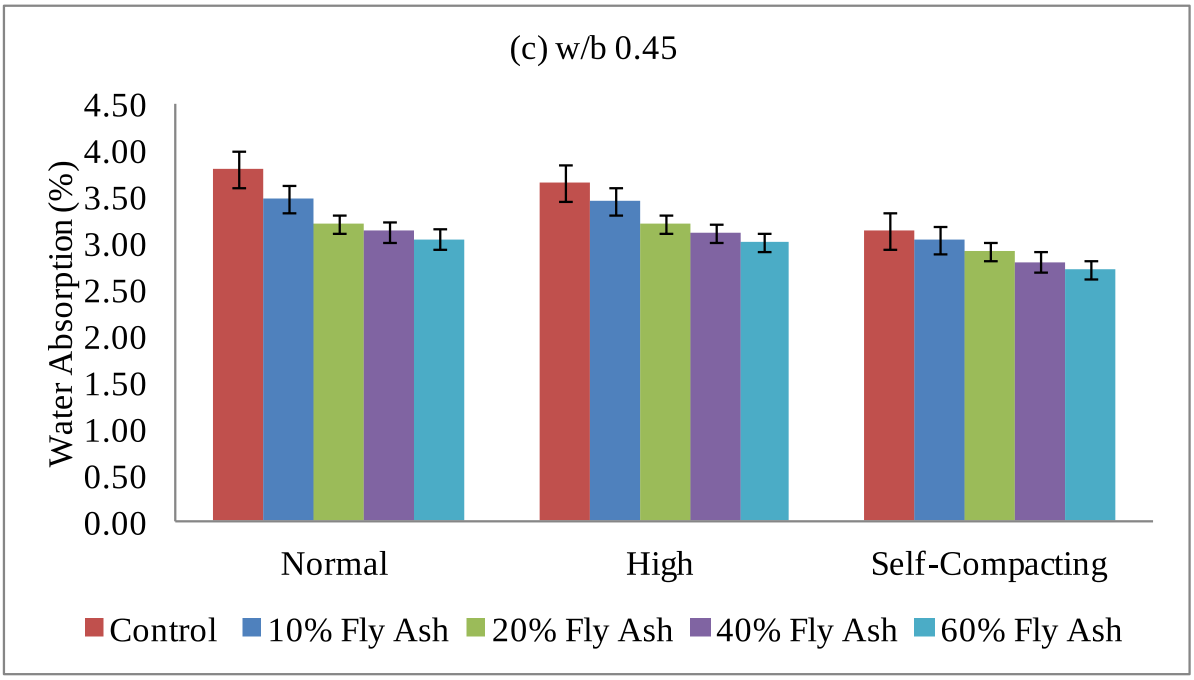


Figure 4.13 Water absorption at w/b 0.45

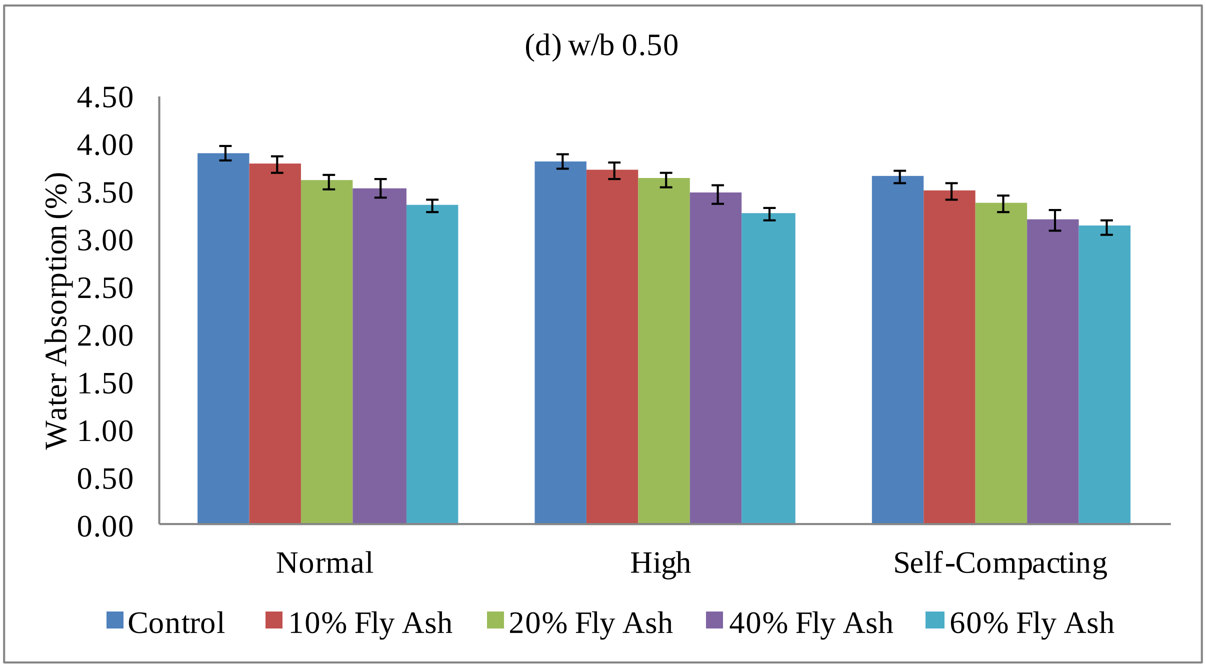


Figure 4.14 Water absorption at w/b 0.50

4.1.3.2 Relative Water Absorption

The relative water absorption for the normal, high and self-compacting mixes is illustrated in Figure 4.15. It is clearly seen that none of the mixes exceed the control line limit as a result of high absorption for the control for all mixes for all w/b ratios. It appears that, at high relative water absorption denotes high in water absorption.

As illustrated in Figure 4.15, the normal mixes produced similar trends of higher relative absorption for each mix at a higher w/b ratio compared to the control. An equivalent decrease was noted for mortar specimens with 10%, 20%, 40% and 60% fly ash content. Nevertheless, it was also observed that there was a similar relative absorption for 40% replacement of fly ash for w/b ratios 0.35, 0.40 and 0.45, which may be due to the addition of fly ash resulting in a lower rate of water absorption.

High mixes illustrate parallel trends, while normal mixes with a higher w/b ratio showed low relative absorption, especially at a high replacement level. The w/b ratio of the mortar with fly ash replacement was high, resulting in low relative absorption due to the fact that the water absorbed by the fly ash is believed to have spilled out of the pores during the mixing process. There was a noticeably lower absorption for w/b ratio 0.45 with 20% fly ash replacement, which occurred due to the large variation in water absorption from 10% to 20% for the w/b ratio 0.45 at high flow mixes.

A different pattern was found for the self-compacting mixes with a w/b ratio of 0.45. This mix showed a high value of water absorption, which varies from the normal and high flow mixes. However, a similar trend of water absorption was obtained whereby the 10% replacement gave the highest value followed by 20%, 40% and 60% fly ash. At the maximum fly ash substitution (60%) level, the voids within the mortar matrix are mostly filled leaving very small pores that obstruct the water passage through the capillaries. The decrease in porosity marks the inferior total water absorption by capillarity, while the smaller pore size may decrease the absorption rate (Braga et al., 2012).

It was observed for normal flow mixes that with the addition of 10% fly ash, there was a reduction in absorption of 3% to 8%. Meanwhile, the addition of 20% fly ash showed a reduction in the absorption of 8% to 16%. While an addition of 40% fly ash reduced the absorption level by 9% to 18%. At the maximum addition level of 60%, a maximum reduction of absorption of 14% to 21% was observed compared to the control. High flow mixes gave a reduction in absorption by 2% to 9%, 5% to 12%, 9% to 16%, and 14% to 18% with the addition of 10%, 20%, 40% and 60% fly ash, respectively. Meanwhile, the self-compacting flow produced a decrease of 3% to 6%, 8% to 14%, 11% to 17% and 14% to 19% in absorption when replaced with fly ash. In looking at the overall results, it is clear that the addition of 60% fly ash showed a huge decrease in the absorption level compared to the control specimens. The apparent reason behind this may again be due to the lower porosity ratio within the mortar.

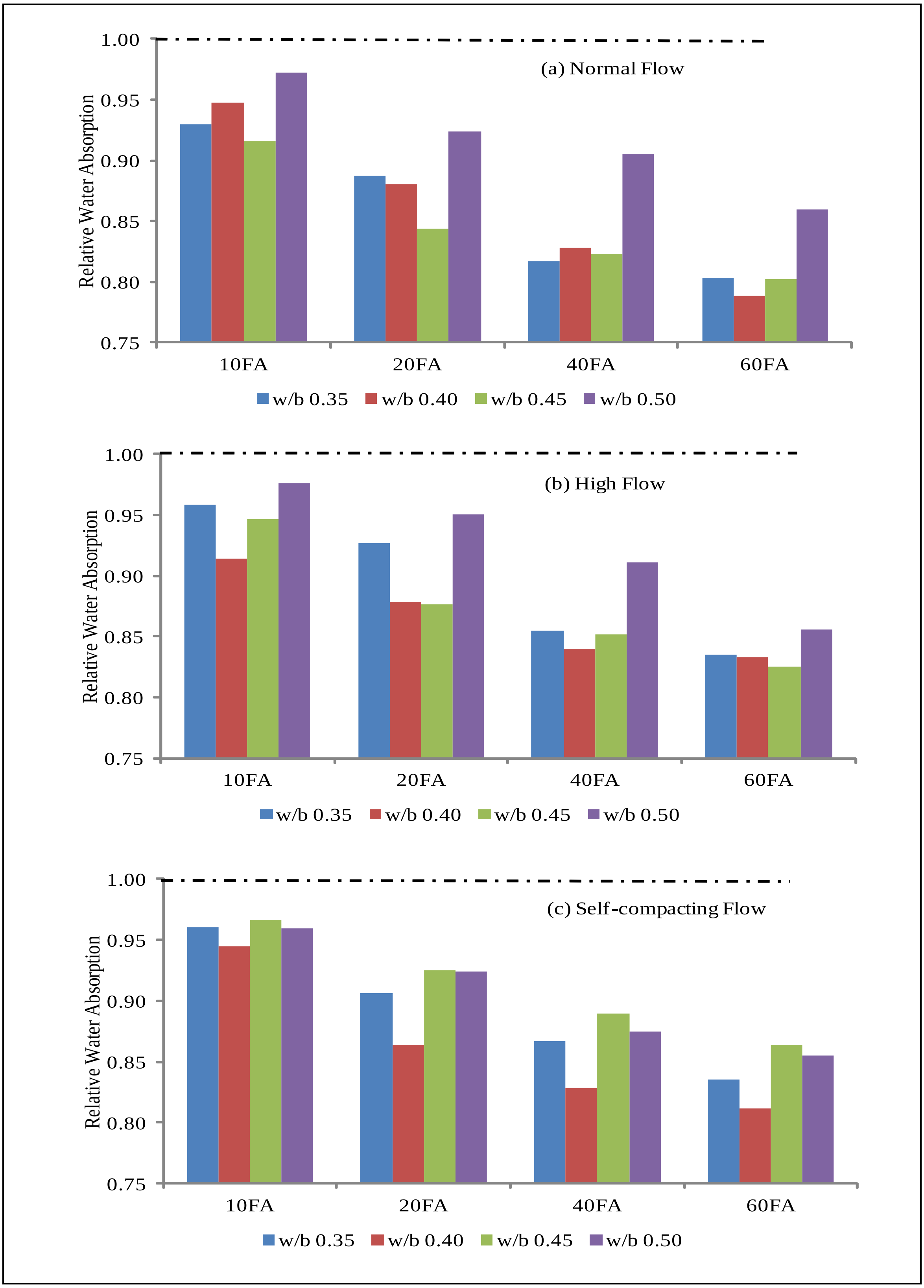


Figure 4.15 Relative Water Absorption

4.1.3.3 Compressive Strength

The compressive strength was determined for mortar cubes (50 x 50 x 50) mm at the ages of 3, 7, 14, 28 and 90 days. Figure 4.16 to Figure 4.19 show the results for the compressive strength at 3, 7, 14, 28 and 90 days for all different w/b ratios. Each strength value is an average of three tests, and individual values varied within ± 3% of the mean, as given the Appendix

The results showed that there is a significant gain in compressive strength due to the introduction of the mineral admixture. Figure 4.16 exhibits the results for the compressive strength for w/b ratio 0.35. At normal flow with a replacement of 10% and 20% of fly ash, an increase in strength was observed at 3 days compared to the control mixes. For the mix containing 10% fly ash, a higher compressive strength than the control specimens was observed from 3 days onwards. This may be due to the filler effects at the lower w/b ratio with small fly ash replacements. At 28 days, the compressive strength varied from 40 MPa to 75 MPa for the normal mix. However, at the later age of 90 days, the 10%, 20% and 40% fly ash mixes achieved higher compressive strength compared to the control. The mix with a replacement level of 60% fly ash was not found to have any significant increase in strength from 3 days to 90 days.

It was observed that the high flow mix with w/b ratio 0.35 at the early age of 3 and 7 days replacement of fly ash did not give any increase in the strength. However, at 28 days an increase in strength occurred by replacing with 10% fly ash compared to the control. At 28 days for the high workability mixes, the compressive strength varied from 45 MPa to 75 MPa. For the later age of 90 days, only 20% fly ash achieved a higher strength than the control. Nevertheless, a positive increase was observed when replaced with 40% fly ash at 90 days. The apparent reason for this is the fact that the pozzolanic reaction of the fly ash requires a relatively longer time to show the effect on the strength. The self-compacting mixes showed an increase at 7 days onwards for 10% of fly ash compared to the control mixture. The compressive strength at 28 days varied from 50 MPa to 90 MPa, which showed that for the self-compacting mixes, the strength was lower at the early ages and that the strength increment appeared at a later age. It was observed that at the later age of 90 days, the 10% and 20% fly ash replacement achieved a higher strength than the control.

The fly ash replacement level up to the maximum level of 60% did not produce any major difference in the development of strength, as the strength obtained was lower for each age regardless of the type of flow. This was also highlighted by Bentz et al. (2011) who found that high volume fly ash is an effective approach for reducing the cement content. However, it is known to have some disadvantages such as reducing early strength and dramatically increased setting times. Several researchers report that the use of mineral additives in the self-compacting mortar results in a significant decrease in the compressive strength (Şahmaran et al., 2006).

The compressive strength for w/b ratio 0.40 is illustrated in Figure 4.17. For the normal, high and self-compacting mixes, it is clear that the replacement with fly ash did not give a rise in strength from the early age of 3 days until the later age of 90 days. The control mixes produced higher strength from 3 days onwards. The mix with 20% fly ash replacement was found to have a sudden decrease in strength at 14 days for all mixes. However, 60% of the fly ash replacement still maintained the lowest strength from 3 days onwards. The compressive strength at 28 days for normal mixes varied from 25 MPa to 70 MPa. While the high and self-compacting mixes had a strength range of between 30 MPa and 75 MPa.

Figure 4.18 illustrates the compressive strength for w/b ratio 0.45. A similar trend line was observed when compared to the other w/b ratios. For normal mixes, 10%

fly ash replacement achieved a higher compressive strength than the control mixture from 3 days onwards. A large variation in strength was observed for the 20% fly ash substitution. The compressive strength at 28 days varied between 30 MPa and 60 MPa. For high and self-compacting mixes, only 10% replacement of fly ash was observed to achieve a higher strength at 7 days compared to the control. The 28 days compressive strength of the high and self-compacting mixes varied from 30 MPa to 65 MPa.

The results for the compressive strength of the mortar mixes with w/b ratio 0.50 are shown in Figure 4.19. A parallel trend line was observed for the normal, high and self-compacting mixes. For the normal, high and self-compacting mixes, it was noticed that the fly ash replacement did not provide any increment in strength from early age, 3 days, until later age, 90 days. However, the control mixes produced a higher strength from 3 days onwards. The variation in compressive strength at 28 days for w/b ratio 0.50 was found to be the lowest among the others with the normal mixes giving 30 MPa to 40 MPa, high mixes 35 MPa to 45 MPa and self-compacting mixes 40 MPa to 55 MPa.

It was observed that the strength development for the control mixture is theoretically dependent on the rate of cement hydration. On the other hand, the addition of fly ash as a mineral admixture is related to the combination effect of cement hydration and pozzolanic reaction. The pozzolanic reaction takes a relatively longer time to produce enhancement in the strength. The dilution effect is more dominant for mixes with a w/b ratio of 0.35 in terms of the enhancement of strength, which is proportional to the addition of mineral admixture. However, this did not have a significant effect for the other w/b ratio mixes.

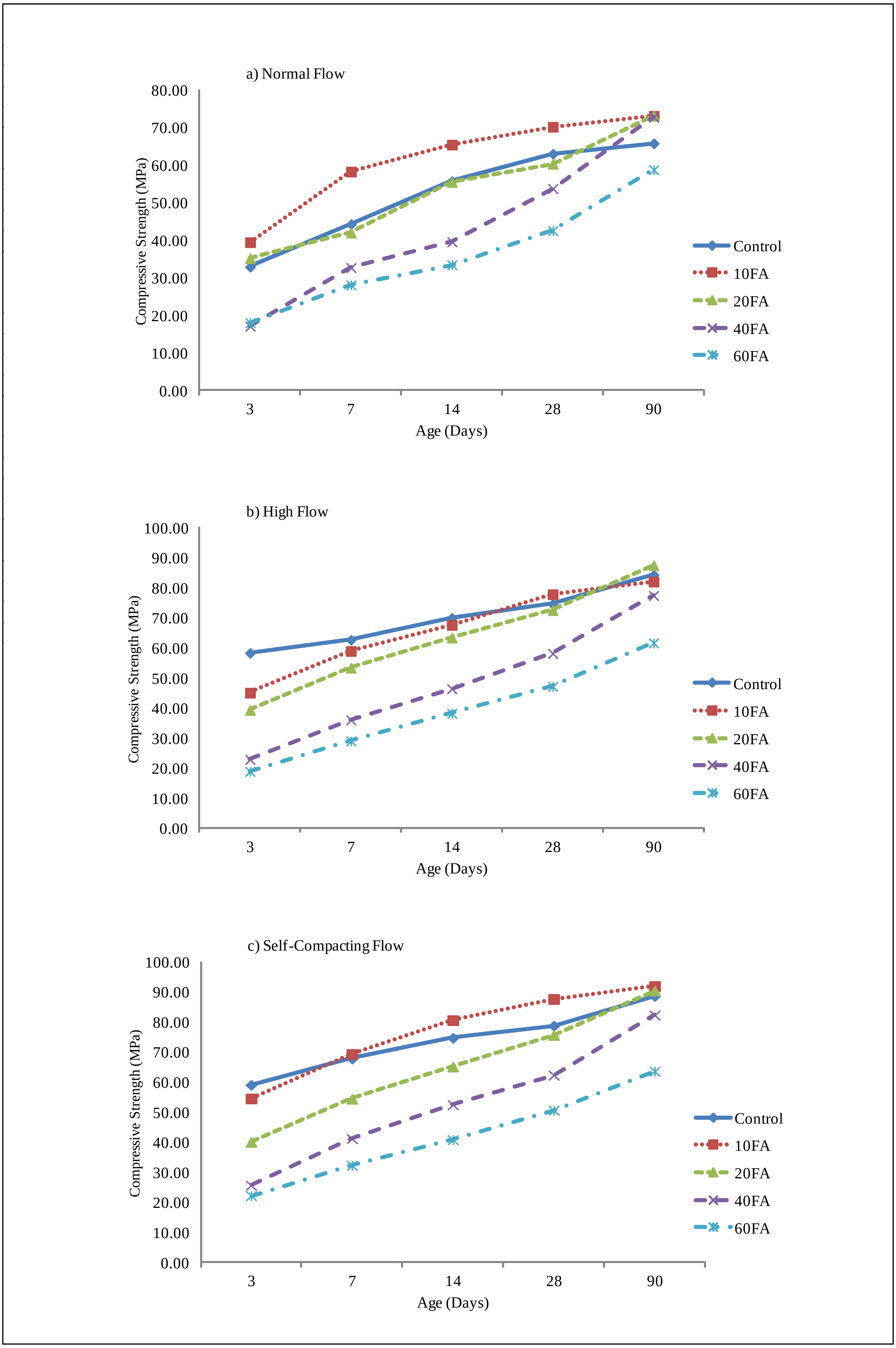


Figure 4.16 Compressive strength w/b 0.35

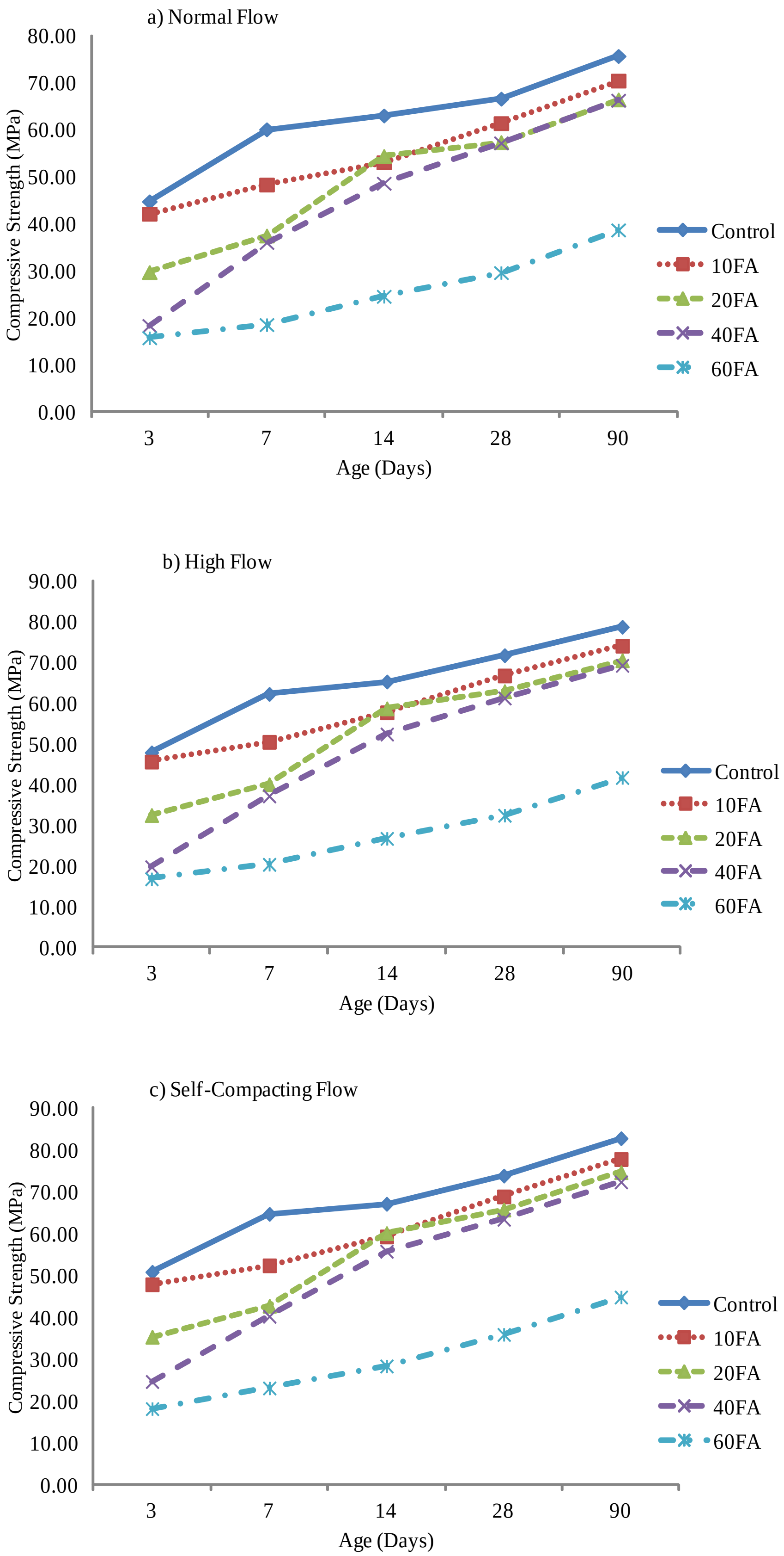


Figure 4.17 Compressive strength w/b 0.40

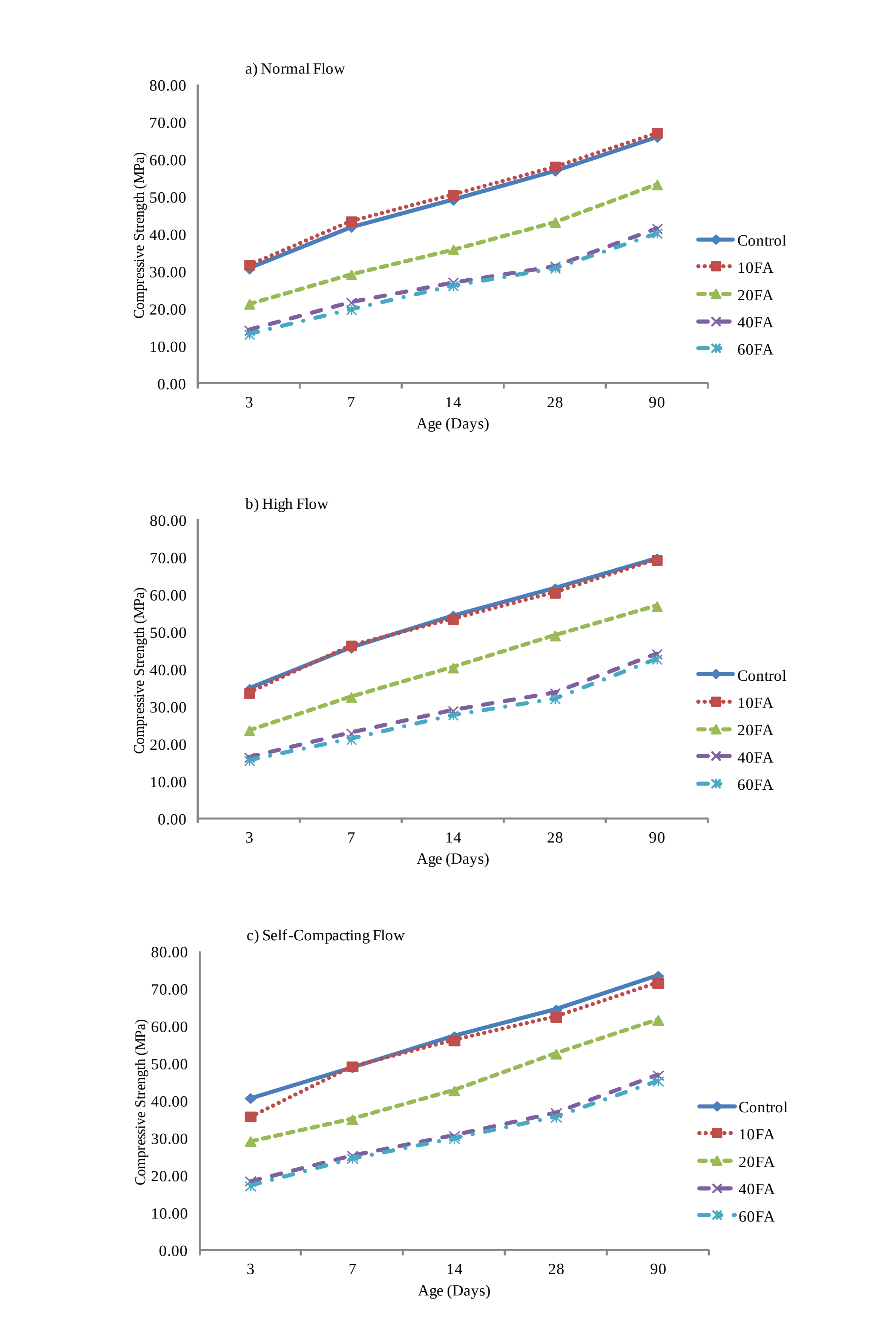


Figure 4.18 Compressive strength w/b 0.45

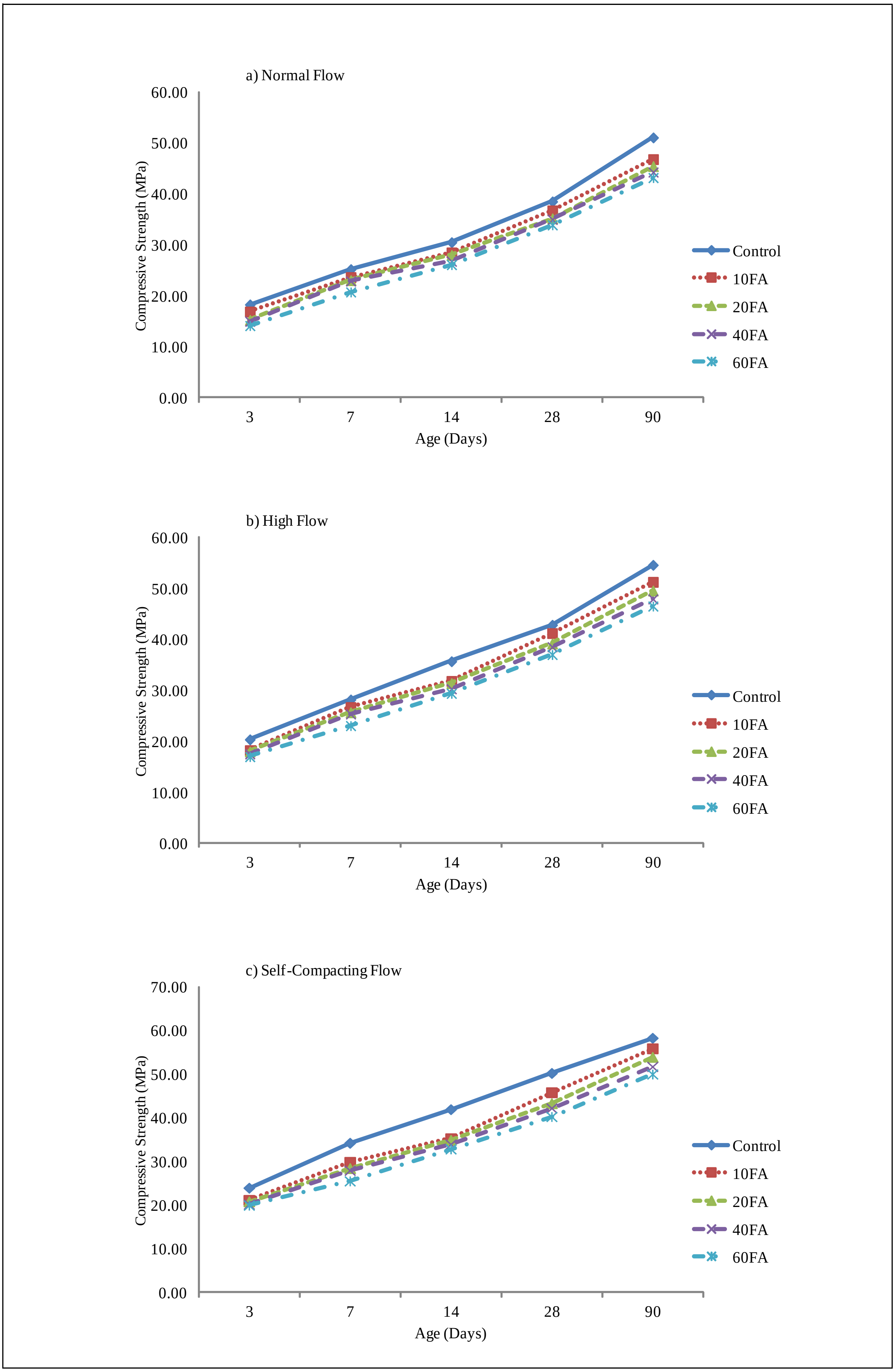


Figure 4.19 Compressive strength at w/b 0.50

4.1.3.4 Relative Compressive strength

The relative compressive strength plot is defined as the ratio of the strength of the fly ash mixture to the control mixture at any particular age. The relative strength plot provides a comprehensive understanding of the rates of reaction in a blended pozzolanic system relative to the plain control system. Figure 4.20 exhibits the relative compressive strengths for w/b ratio 0.35.

The enhancement of strength indicates similar trends for all the flow mixes for w/b ratios 0.40, 0.45 and 0.50 (Appendix 4 to 6). Generally, it can be seen that at normal flow mixes, only 10% and 20% fly ash replacement produced early strength enhancement, with 10% fly ash achieving a higher relative strength from 3 days onwards. Nevertheless, the strength continued to show an increment whereby at 10%, 20%, 40% there was an enhancement of strength at the later age of 90 days. The high flow mixes and self-compacting flow mixes did not produce an early strength enhancement, which may be due to the filler effect and acceleration process of cement hydration. Instead, a decrease in the compressive strength at the early ages was observed in which the reduction was proportional to the replacement level.

With the addition of mineral admixture, an immediate dilution effect results whereby the early strength reduces in an approximate proportion to the degree of replacement. However, if the admixture is finely divided, it behaves as a micro filler to increase the early strength through efficient packing, higher density and more homogeneous initial transition zone. The presence of finely divided particles also has an acceleration effect on cement hydration. Moreover, if the finely divided mineral admixture possesses pozzolanicity, then the lime consumption and formation of additional cementitious gels will further increase the strength by pore-refinement to provide some improvement in the microstructure of the transition zone.

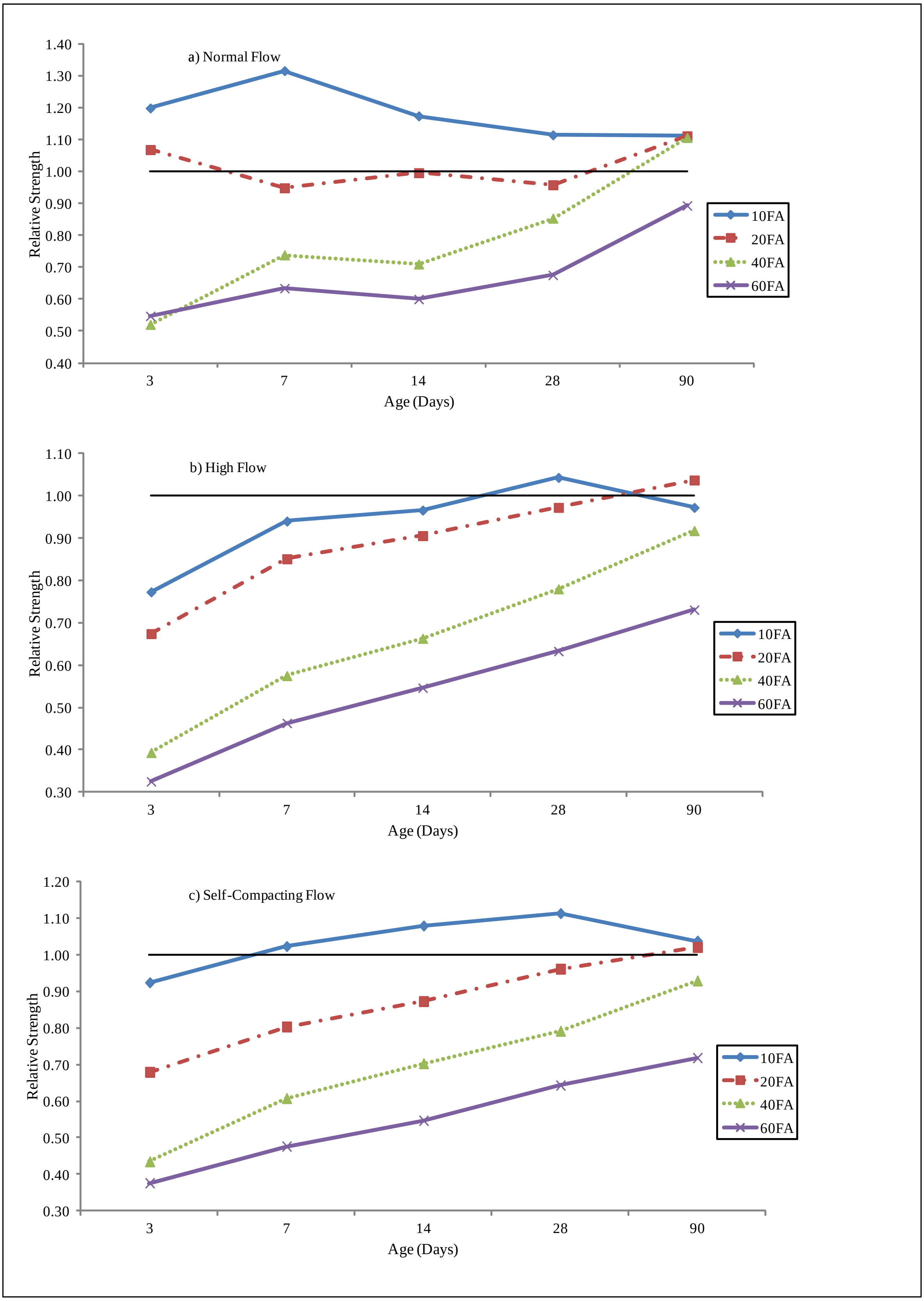


Figure 4.20 Relative strength at w/b 0.35

4.2 Environmental Impact

The approach by (Henry, Pardo, Nishimura, & Kato, 2011) in calculating the CO_2 footprint of concrete when using recycled aggregate have been adopted in ascertaining the environmental sustainability performance of the mortar mixes. CO_2 footprint was determined for the mortar mix proportions together with CO_2 emission inventory data which represent the embedded CO_2 values from cradle to grave of each constituent material as proposed by Soo (2011) in his study.

CO_2 footprint of self-compacting mixes for each w/b ratios is presented in Figure 4.21. It was reported by (Flower & Sanjayan, 2007) that CO_2 released related to the manufacturing of concrete admixtures are limited. Total amount of admixtures add in to a mixture is commonly not more than two litres per cubic metre. Therefore, the effects to the total CO_2 released per cubic metre concrete is regard as insignificant. Thus, the CO_2 produce by admixtures can practically exclude in the calculations of total CO_2 released. Therefore in this discussion, only self-compacting flow mixes will be reported since there is only a small difference of CO_2 emission for superplasticizer, while the other constituent materials are the same. In general, the best environmental performance is achieved through a low CO_2 footprint that shows the decrease of percentage for CO_2 emission to the environment.

A linear trend was observed for all w/b ratios throughout every mixes. The linearity of the plots shows that the reduction of CO_2 footprint is proportionate with reduction of w/b ratio and amount of fly ash replacement. From the figure, it clearly shows that when comparing the CO_2 footprint with the control mixes, it is assumed that 100% of CO_2 emission was released for the control mixes (100% of ordinary Portland cement gives 100% of CO_2 releases), illustrating a significant decrease in trend. At 10% fly ash replacement gave 9.42% less of CO_2 than control, followed by 20% of fly ash replacement at18.85%, 40% of fly ash replacement at 37.69% and at 60% of fly ash replacement recorded the highest decrease of 56.54%.

Positive observation shows that by replacing fly ash to a maximum level of 60%, it provides the best CO_2 footprint reduction with a decrease of more than 50% CO_2 footprint when compared to others. The figure shows that at maximum level of fly ash replacement of 60% gave the lowest CO_2 footprint compared to control, 10%, 20% and 40% fly ash replacement which is synchronous with the statement which states that "to reduce the CO_2 emission in concrete mixes, the cement content can be minimized and replaced with other minerals" (Fantilli & Chiaia, 2013). This approach is beneficial to concrete manufacturers or producers since it will help in reducing CO_2 impact on the environment. Thus, it will promote environmental and economical sustainability by reducing the CO_2 footprint and cost savings through waste materials utilization.

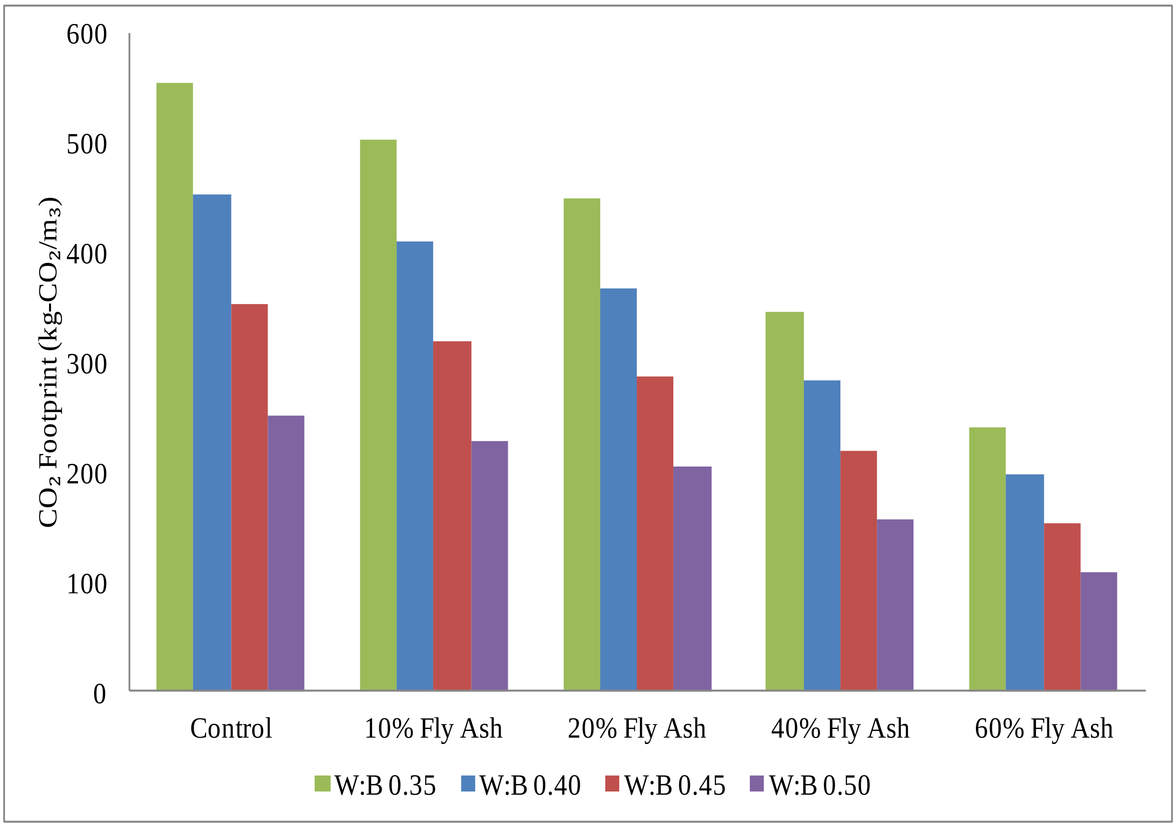


Figure 4.21 CO_2 footprint of self- compacting mixes

4.2.1 Compressive Strength versus Environmental Sustainability

Best-fit plots for the relationship between of 28 days compressive strength and CO_2 footprint for normal, high and self-compacting flow are shown in Figure 4.22. The plots were used to predict the CO_2 footprint from the known values of 28 day compressive strength. It is observed from the figure that with the increase in strength, a linear relationship can be obtained between 28 days strength and CO_2 footprint. Linear equations established for each of type flow are as follow:

Normal flow

$$Y = 0.1005x + 17.525 \ (R^2 = 0.8348) \qquad \textit{(Equation 4.1)}$$

High flow

$$Y = 0.1134x + 18.166 \ (R^2 = 0.8816) \qquad \textit{(Equation 4.2)}$$

Self-compacting flow

$$Y = 0.1195x + 20.167 \ (R^2 = 0.8961) \qquad \textit{(Equation 4.3)}$$

Where: Y is compressive strength at 28 days and X is CO_2 footprint

From the equations obtained from the plot, it is clear that an increase in gradient of the curve produced much higher range of 28 days for all the mixes. A variation in strength between 25 MPa to 75 MPa, 30 MPa to 75 MPa and 30 MPa to 90 MPa was observed for normal, high and self-compacting flow mortars respectively. Greater difference in strength was obtained for self-compacting mixes. It was observed that the coefficient of regression (R^2) established for 28 day strength and CO_2 footprint for each of the mixes produced a good correlation with an average of 0.8752. However, the linear equation established between 28 day compressive strength and CO_2 footprint was only relevant for w/b ratio 0.35 to 0.50 with normal, high and self-compacting flow.

A direct relationship was found between the 28 day compressive strength and CO_2 footprint. Lower CO_2 footprint showed lower strength of achievement and vice versa. Interestingly, self-compacting flow seems to give better strength yet with a low CO_2 footprint.

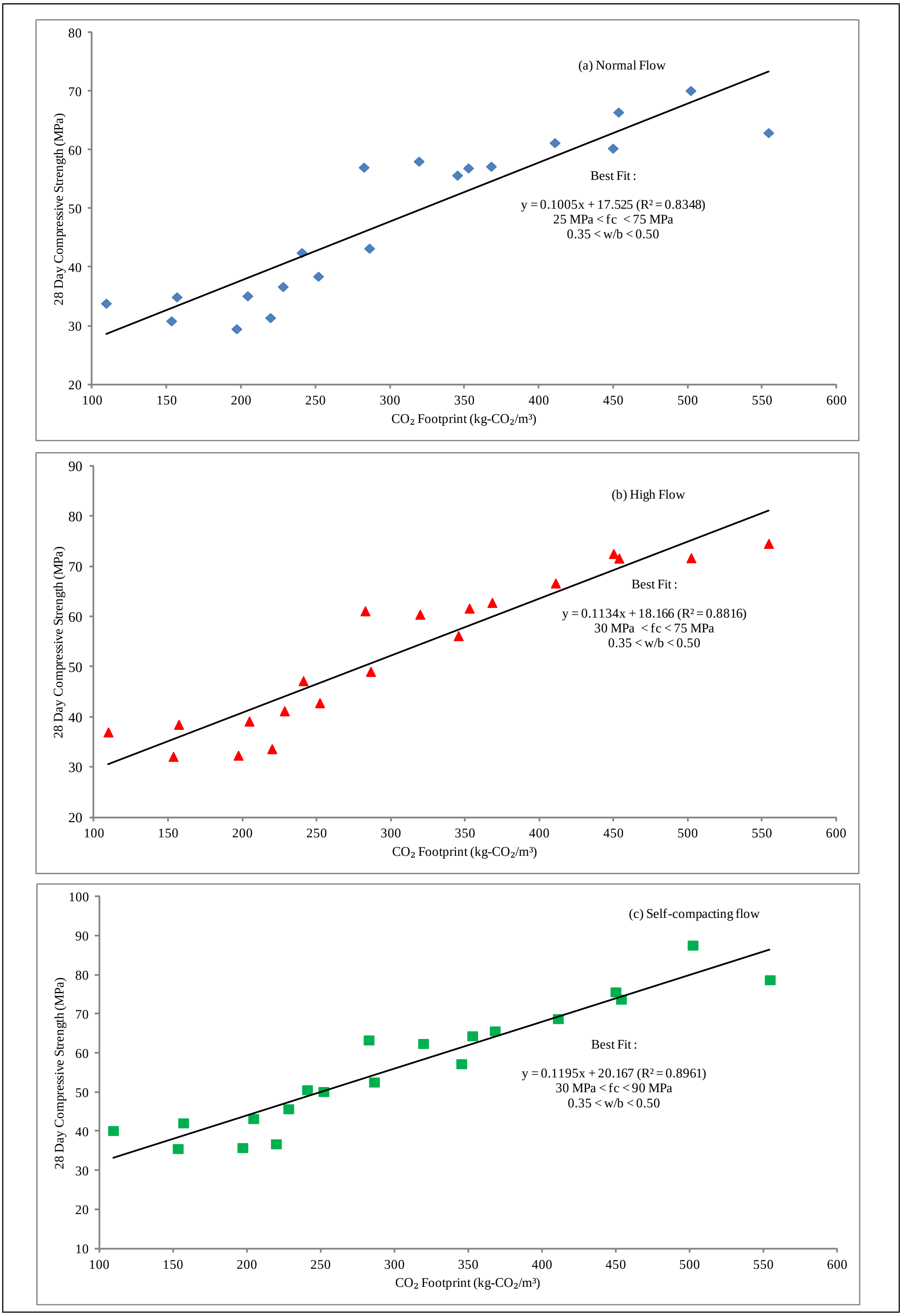


Figure 4.22 Strength to environmental sustainability

4.2.2 Durability versus Environmental Sustainability

Water absorption is an indicator of durability; the lower water absorption is attributed to lower w/b ratio and better durability. In this study, the self compacting mortars with 60% of fly ash replacement have greater water absorption capacity. (Dinakar et al., 2008) addressed that SCC with addition of high-volume fly ash are high permeable and water absorption. (BouzoubaaÃa, 2000) reports that concrete that were replaced by 55-60% by Class F fly ash established excellent mechanical and durability properties. The increase in paste volume due to the lower specific gravity of fly ash contributes to an increased capillary pore volume and increased water absorption (Dinakar et al., 2008).

Figure 4.23 to Figure 4.26 shows the relationship between water absorption and environmental sustainability impact in terms of CO_2 footprint for all w/b ratios for normal, high and self-compacting flow mixes. Generally, it is observed that a positive linear relationship can be established between the components at all w/b ratios for every type of flow mixes.

Figure 4.23 shows the relationship of both variables for w/b 0.35. From the smaller gradient of linear equations gathered, a lower absorption rate is achieved with a similar CO_2 footprint value. Observation shows that the dominant factor in determining the relationship between durability and environmental sustainability is highly dependent on the w/b ratio rather than the type of flow. Low w/b ratio seems to provide better performance in terms of durability as it will have fewer pores specifically with the addition of minerals admixture. From the analysis carried out it can be concluded that self-compacting flow gave the lowest water absorption with lowest CO_2 footprint.

The relationship between durability and environmental sustainability for w/b ratio 0.40, 0.45 and 0.50 produced a very much similar trend. With the establishment of linear equations, it shows similar trend throughout all w/b ratios whereby lower slope of each type of mixes will give a low absorption rate with low CO_2 footprint. However, a significant decrease for few data of absorption was observed which was discussed earlier in relative water absorption. From the linear relationship, it can be denoted that there exists a strong correlation specifically for self-compacting flow. Based on the figure, durability has a direct proportion relationship to environmental sustainability, since at low CO_2 footprint (less environmental impact) will give low water absorption (better durability), and vice versa.

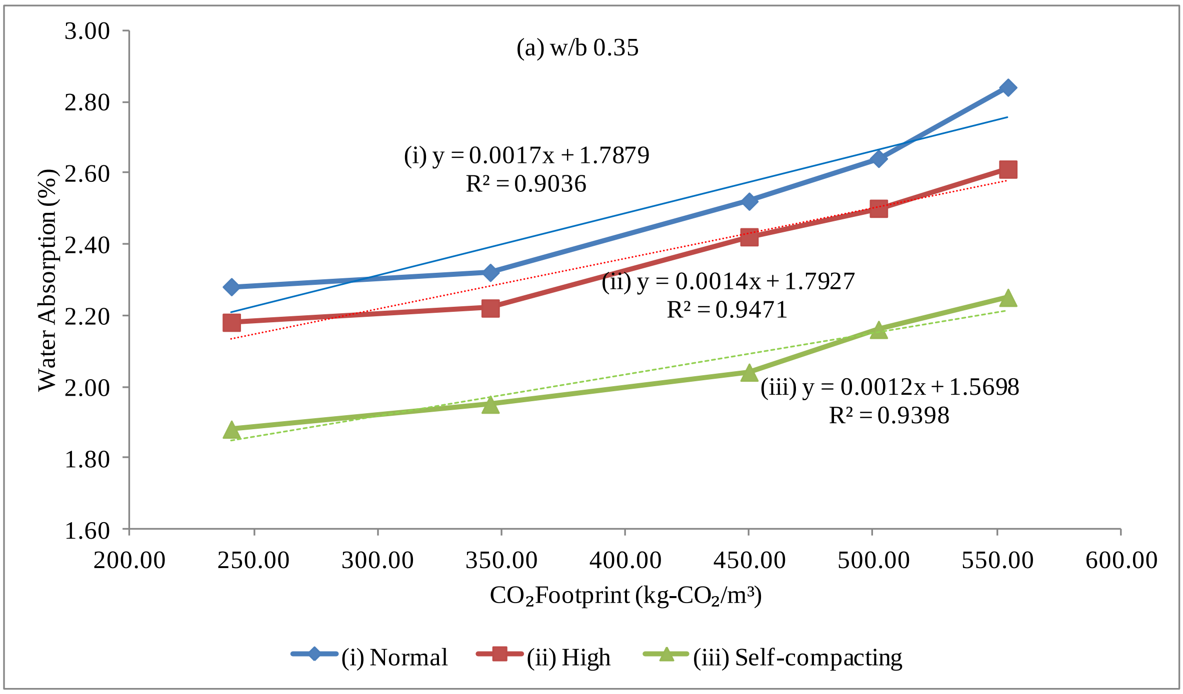


Figure 4.23 Durability to sustainability performance w/b 0.35

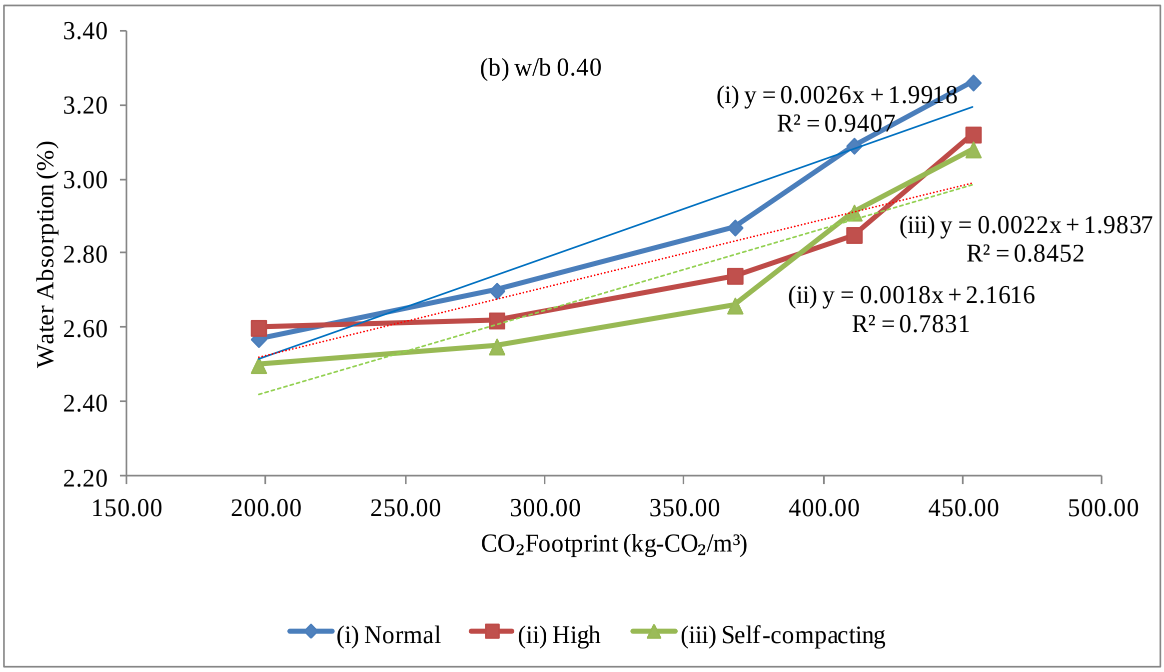


Figure 4.24 Durability to sustainability performance w/b 0.40

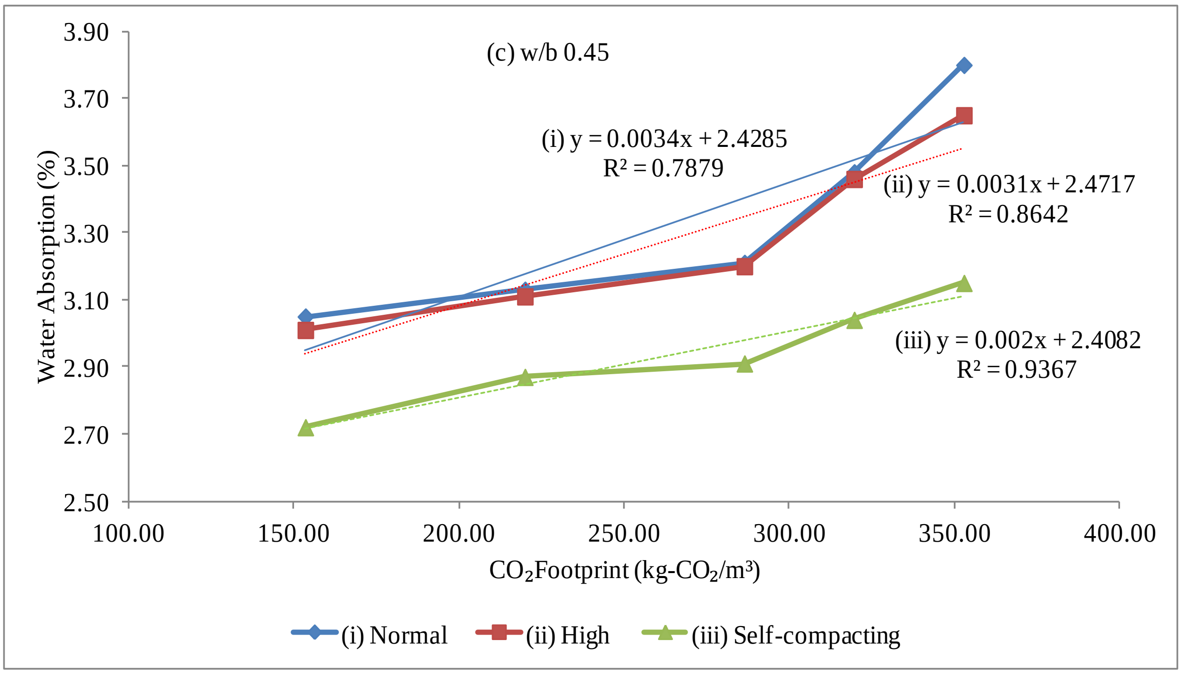


Figure 4.25 Durability to sustainability performance w/b 0.45

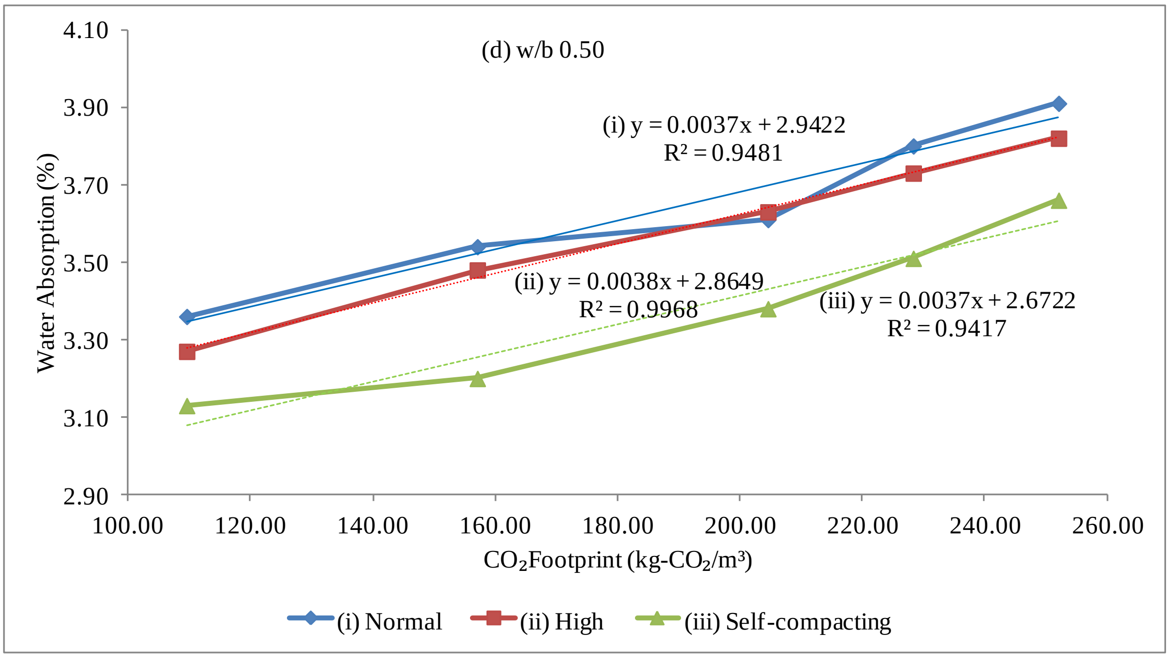


Figure 4.26 Durability to sustainability performance w/b 0.50

4.3 Performance index

Performance index is defined as the ratio between the CO_2 released and the mechanical properties of the samples. The performance index will be able to provide some comprehensive information on the balance between environmental sustainability and engineering performance. (Fantilli & Chiaia, 2013) proposed an equation to relate both the components as stated below.

$$I = \frac{CO\ \ Released}{Mechanical\ Properties}$$

Based on the equation developed by (Fantilli & Chiaia, 2013), the quantitative measures is generally by looking at the I value (performance index). Based on the equation developed by (Fantilli & Chiaia, 2013), the quantitative measure is basically depends on the I value. Several researcher (Damineli et al., 2010; Fantilli & Chiaia, 2013; Kayali & Sharfuddin Ahmed, 2013) have made an attempt produce their own performance index. (Fantilli & Chiaia, 2013) introduced the ecological-mechanical performances of concrete which measures new index between the quantity of CO_2 released by the manufacture of cement and fibres and the fundamental mechanical indicators (strength and ductility).

4.3.1 Performance index (Compressive Strength – Environmental Sustainability)

An approach proposed by (Fantilli & Chiaia, 2013) in measuring the index ratio (I-ratio) of mechanical properties and ecological properties of self-consolidating concrete (SCC) was adopted in this study in deriving the performance index between the engineering properties i.e. strength and durability and environmental sustainability impact i.e. CO_2 footprint.

Performance index for strength and durability to the environmental sustainability was compared through their relative performance index. Figure 4.27 shows the relative performance index of compressive strength at 28 day and CO_2 footprint for different flowability. Generally, best environmental-mechanical performances will be achieved when the performance index is the lowest. (Kayali & Sharfuddin Ahmed, 2013) considering their mechanical and durability property performance as 1.0, which demonstrate its performance is comparatively lesser to OPC control or more than 1.0. This brought to attention that the concrete is shows improved result than OPC concrete.

Same indicator of 1.0 for opc mortar (control), as proposed by (Kayali & Sharfuddin Ahmed, 2013) was adopted while comparing relative performance index of strength to environmental sustainability. It was observed that 10% fly ash of high flow mixes shows a better performance with respect to strength and environmental sustainability that produced relative performance index at 0.94 that is less 6% to achieve index 1.0. A sudden decrease was observed at 60% fly ash that produced 0.64, 36% less to reach 1.0 which shows an inferior performance at this particular replacement level.

Besides that, mixes with w/b 0.45 for normal flow shows better performance while produced higher relative performance index at 40% replacement of fly ash of 1.13 which is 0.13% more compared to opc mortar specimens. Referring to the Figure, replacement of fly ash at high percentage i.e. 10% was observed to give the best performance index in terms of strength and environmental sustainability components because at lower w/b ratio 0.35, 10% fly ash was exhibiting higher performance index of 0.94.

Similar observation was attained at high and self-compacting flows whereby at 60% of fly ash replacement, an inferior value of performance index of 0.50 and 0.54 obtained for high and self-compacting flow respectively. Maximum value of relative performance index is indicated 1.14 at w/b 0.45 for high flow mix at 40% replacement of fly ash. Lowest performance index was gathered for 60% repalcement of fly ash throughtout the flow. Similar findings was also obtained by (Fantilli & Chiaia, 2013), since they reported to achieve lowest performance index ratio at self-compacting concrete with addition of fly ash and silica fume compared to plain self-compacting concrete. (Kayali & Sharfuddin Ahmed, 2013) also reported that the lowest performance index while concrete is added with fly ash in high percentage i.e 50% replacement.

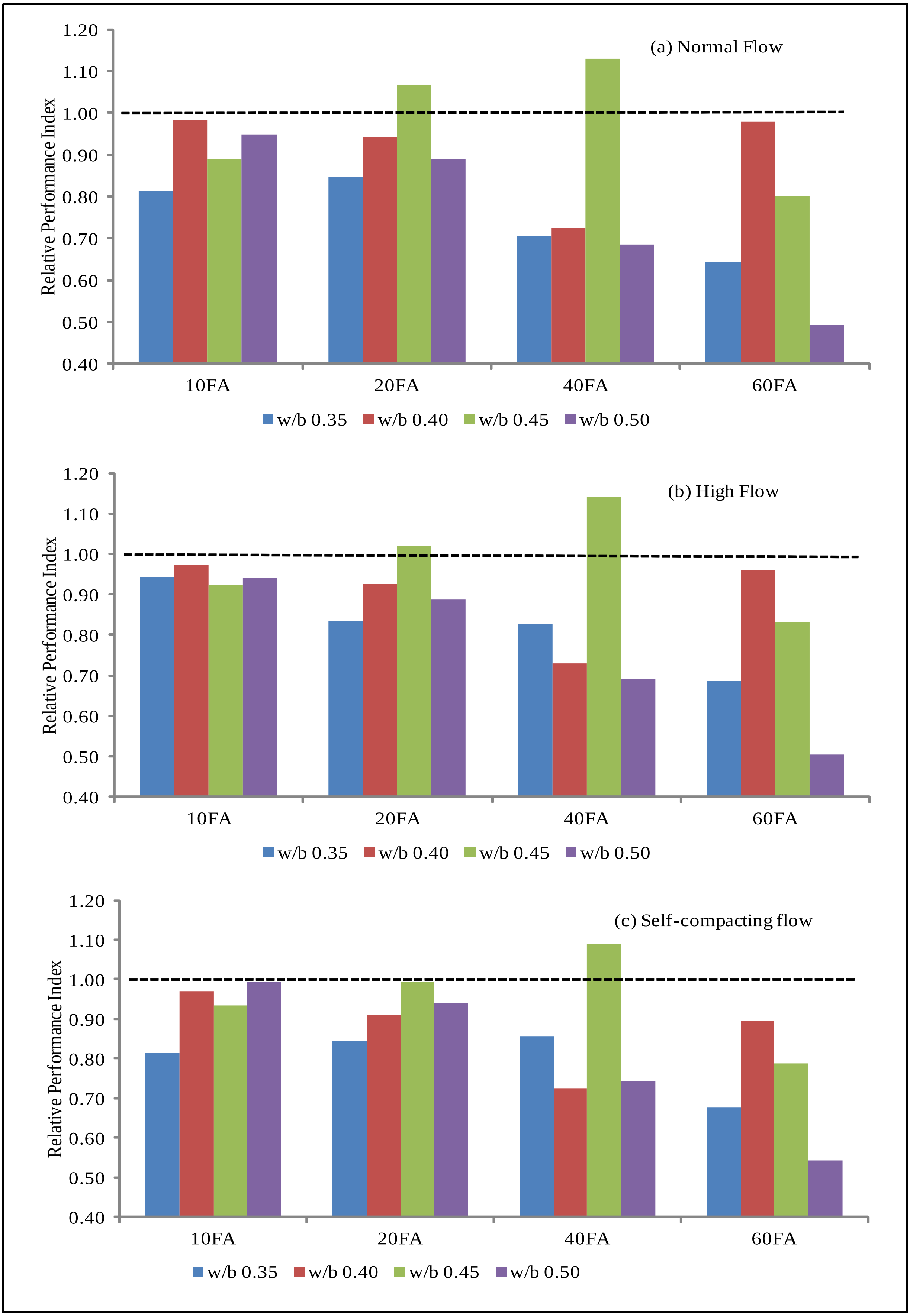


Figure 4.27 Relative performance index of strength -environmental sustainability

4.3.2 Performance index (Durability – Environmental Sustainability)

Similar approach was adapted for the evaluation of durability performance and environmental sustainability. Figure 4.28 shows the relative performance index of durability and environmental sustainability for different flowabilities. While comparing the durability performance to the environmental sustainability components, the relative performance index produces a linearity at every w/b ratios i.e 0.35, 0.40, 0.45 and 0.50. The result somehow show only a marginal difference for each group of w/b ratios in terms of durability and environmental sustainability. This suggests that the replacement of fly ash affects more the difference in relative performance index.

As noticed in Figure 4.28, 10% and 20% replacement level of fly ash shows better performance in terms of durability to environmental sustainability averagely 8% to reach 1.0 index. Significantly, at 60% replacement level, shows the inferior performance that is 50% to achieve index at 1.0.

Durability seems to have a direct relationship to CO_2 footprint since at maximum level of replacement i.e. 60% fly ash, an ideal environmental impact obtained. By replacing cement content up to the maximum level, there is a high possibility of reducing CO_2 footprint of concrete to lower significantly the environmental impact. However, (Henry et al., 2011) have further highlighted that by replacing cement with other materials, it should not only achieve better strength at 28 day, but the durability aspect should also be improved and can function together in reducing the environmental impact.

Replacing fly ash up to 60%, a lower water absorption and CO_2 footprint properties noticed. However, the strength performances for 60% fly ash were still the lowest at 28 days for all w/b ratios. It was also captured that addition of mineral admixtures gave a better performance index in terms of durability and environmental sustainability components.

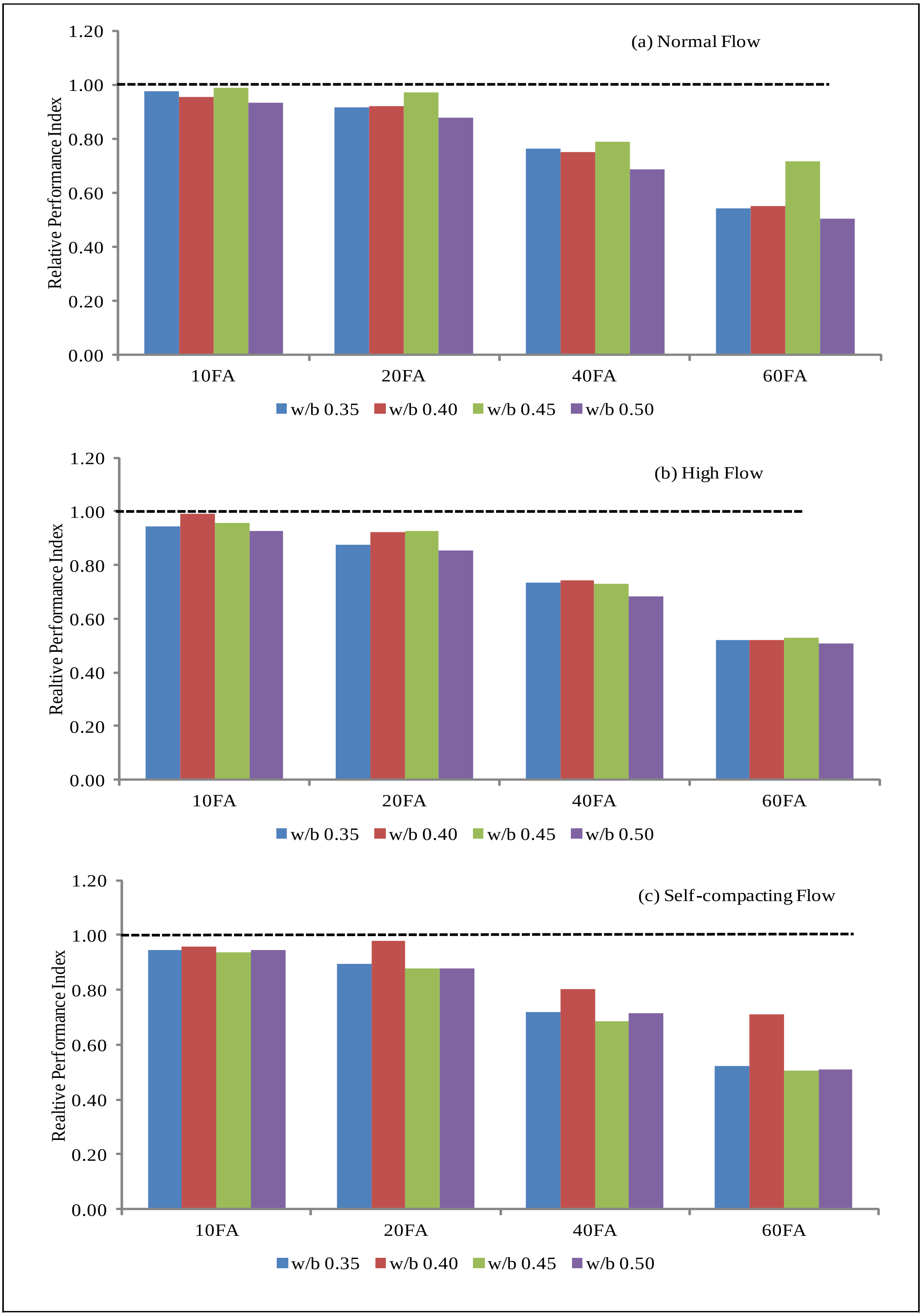


Figure 4.28 Relative performance index of durability -environmental sustainability

4.4 Cost Factor

Economic sustainability evaluation was determined through the cost factor evaluation. Cost factor evaluation for this research was determined solely by the end product of the materials engaged for the production of mortar without considering some cost-related aspects such as the source location, energy source and the mode of transport involved. Cost factor is determined at the final stage of this research to make a cost comparison between each of the mortar element to engineering and environmental sustainability performance.

Self compacting mortar (SCM) is an integral part of the design for self-compacting concrete (SCC). SCC is a technological expansion of the conservative concrete, whereby the conventional compaction is no longer required. Though SCC requires preliminary high budget over normal concrete and caused delayed its application in construction, its performance has attracted the whole world with its technology. Therefore, it is practical to try for any substitutions in reducing the cost of SCC (Akram, Memon, & Obaid, 2009). Ability to adapt wide ranges of waste constituents into valuable by-products, SCC is perceived as a possible substitution to a normal concrete. Objective to diminish greenhouse gas emissions by employing waste constituents from the manufacturing of concrete products are the important goal in SCC developments.

Table 4.2 shows the cost of mortar constituents materials per kg obtained from the Department of Statistic Malaysia. The major cost contribution for mixes was found to have been affected by superplasticizer dosage, followed by cement RM 0.31 per kg, fly ash RM 0.10 per kg, fine aggregates RM0.03 per kg and water perceived to be the ones with the lowest contribution to the cost RM 0.002 per kg of concrete.

Figure 4.29 shows the overall cost comparison of three types of mortar of different workabilities with four different w/b ratios. For all water-binder ratios w/b it shows similar trends with the control for any of the mixes giving high cost compared when replaced with fly ash. It was also observed that linear relationship was established for every group of mixes i.e. normal, high and self-compacting flow mixes at every w/b ratios. Superplasticizer of certain percentage was added to achieve the targeted slump flow mixes thus explained the increased cost for the self-compacting flow mixes since it requires more superplasticizer to obtain the slump flow diameter of 25 ± 1 cm as required by EFNARC. The highest cost was noted at w/b ratio 0.35 during control mix of self-compacting flow with RM1.78 per kg of mortar mixes. The lowest cost was obtained when 60% replacement of fly ash at w/b ratio of 0.50 of normal flow with RM0.58 per kg of mortar mixes. Lastly, the decrease in cost with the addition of mineral admixture into the mixes was proportionate for every w/b ratio.

Table 4.2 Cost per kg of mix constituents (Dept.of Statistic Malaysia, 2010)

Material	Cost (RM)	Cost/kg (RM)
Cement	15.25 /50 kg	0.305
Fine Aggregate	34.00 / tonne	0.034
Superplasticizer	330.00 /20 litre	16.50
Fly Ash	100/tonne	0.10
Water	2.00 / m^3	0.002

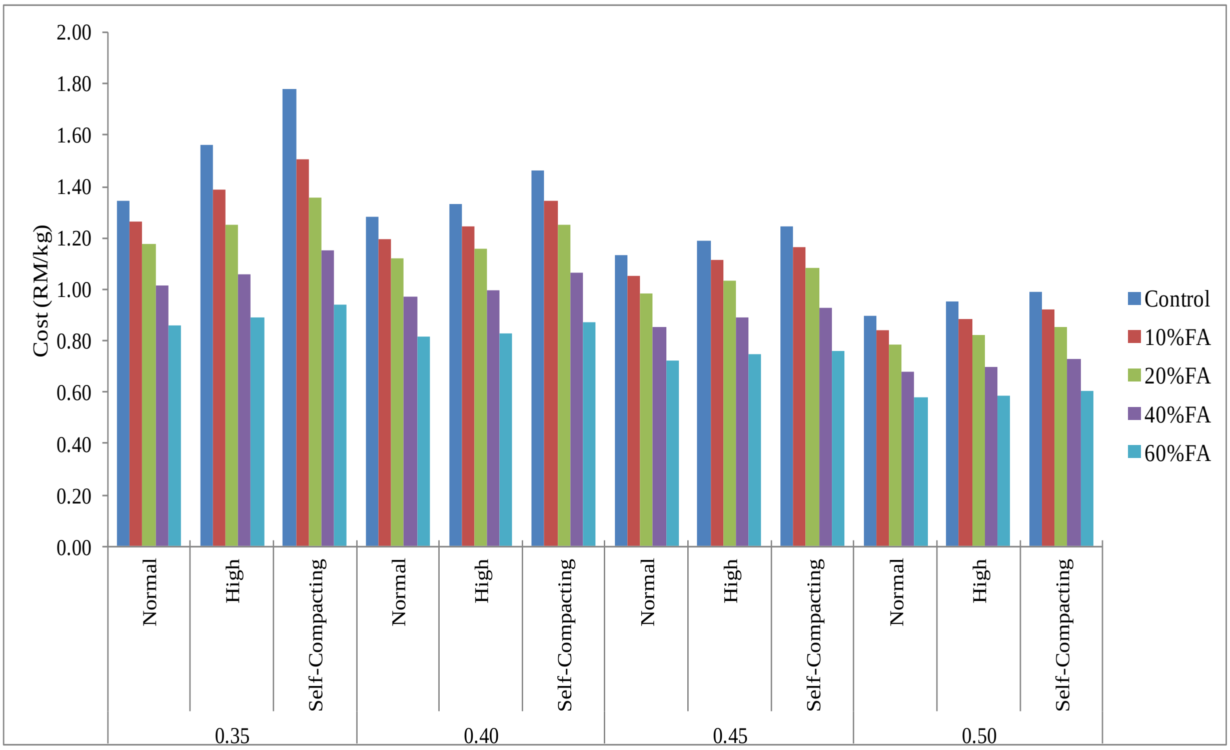


Figure 4.29 Overall cost comparison of mortar with different water/binder ratio

4.4.1 Cost factor versus engineering performances

Cost factor based on cost per kg of mortar and engineering performances based on cost per kg per MPa shows that the cost of each kg of mortar is directly proportional to strength. However, for higher strength, the cost increases. Utilization of additional superplasticizer and cement helps to elevate the 28 days strength. Figure 4.30 to Figure 4.33 illustrates the comparison between cost per kg and cost per kg per MPa of mortar specimens at 28 days. Figures presented covered all types of flow ability and w/b ratios.

Figure 4.30 illustrates the cost comparison of cost per kg mortar and cost per kg per MPa for w/b ratio 0.35. It is observed that control mixes for any type of flow indicate significantly high cost per kg of mortar. Besides that, a linear trend was also obtained throughout the w/b 0.35 mixes with a proportionate decrease in cost per kg of mortar while replacing with mineral admixtures. This was expected earlier because as the cement is replaced by a much cheaper material directly, there will be a reduction in cost (fly ash is about 3 times cheaper than OPC). It was also observed that the cost per kg of mortar for self-compacting flow specimens increased by 44% compared to normal flow. This may be due to the additional requirement in SP dosage to produce highly flowable mortar. This was also expected as the cost of SP is much higher than other materials.

However, by comparing the cost per unit of strength, it is observed that the difference was only marginal particularly at high and self-compacting flow. Normal flow indicated a sudden drop in cost per unit of strength at 10% replacement of fly ash as the highest strength was achieved for this particular mix. From Figure 4.31 to Figure 4.33, cost per unit of weight for w/b 0.40, 0.45 and 0.50 is observed to be linear throughout the flow mixes. It is also observed that the cost per unit of strength for each w/b ratios performed similarly for every flow mix. This denotes that the difference of cost per unit of strength is highly dominated by the replacement of fly ash.

Variation of cost per unit weight and cost per unit strength was found to be low at higher w/b ratio 0.50 for self-compacting flow. This may due to the lesser SP requirement in producing the desired flowability. Comparing the mixture economics for all the three type of flowability, it is found that the self-compacting flow at a much lower percentage of fly ash replacement is more favourable as it provides low cost per unit strength especially at low w/b ratio.

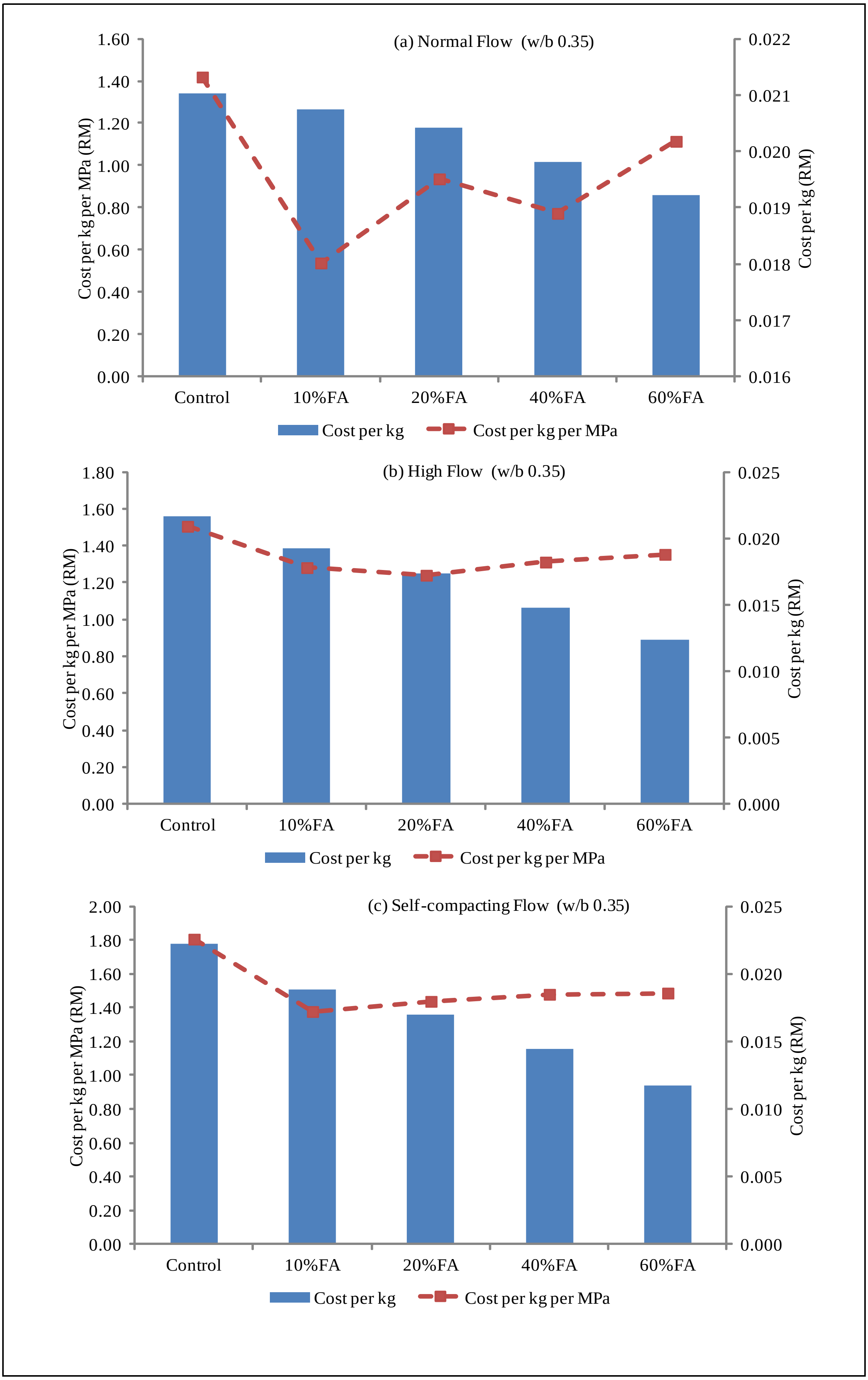


Figure 4.30 Cost-strength for w/b 0.35

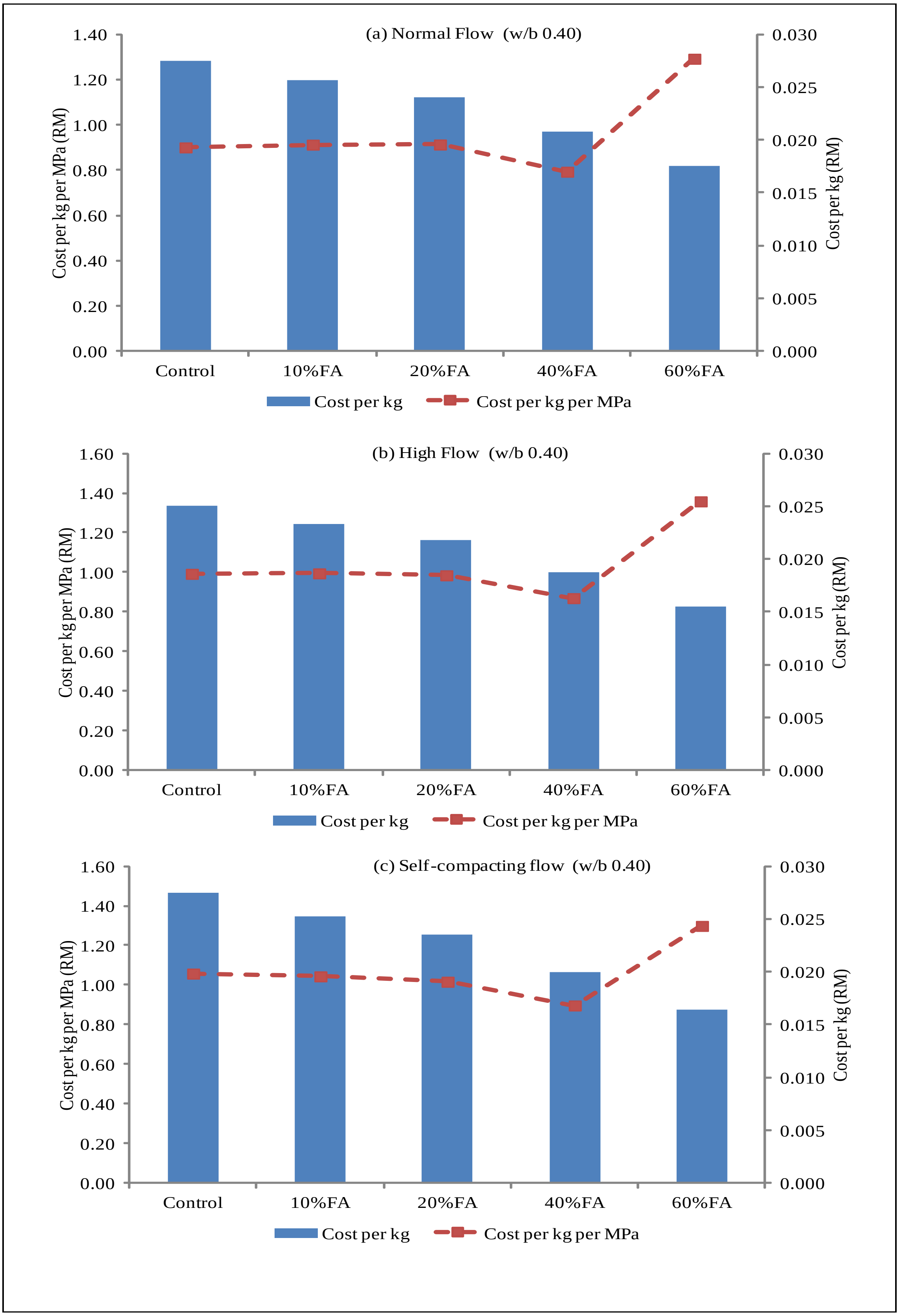


Figure 4.31 Cost-strength w/b 0.40

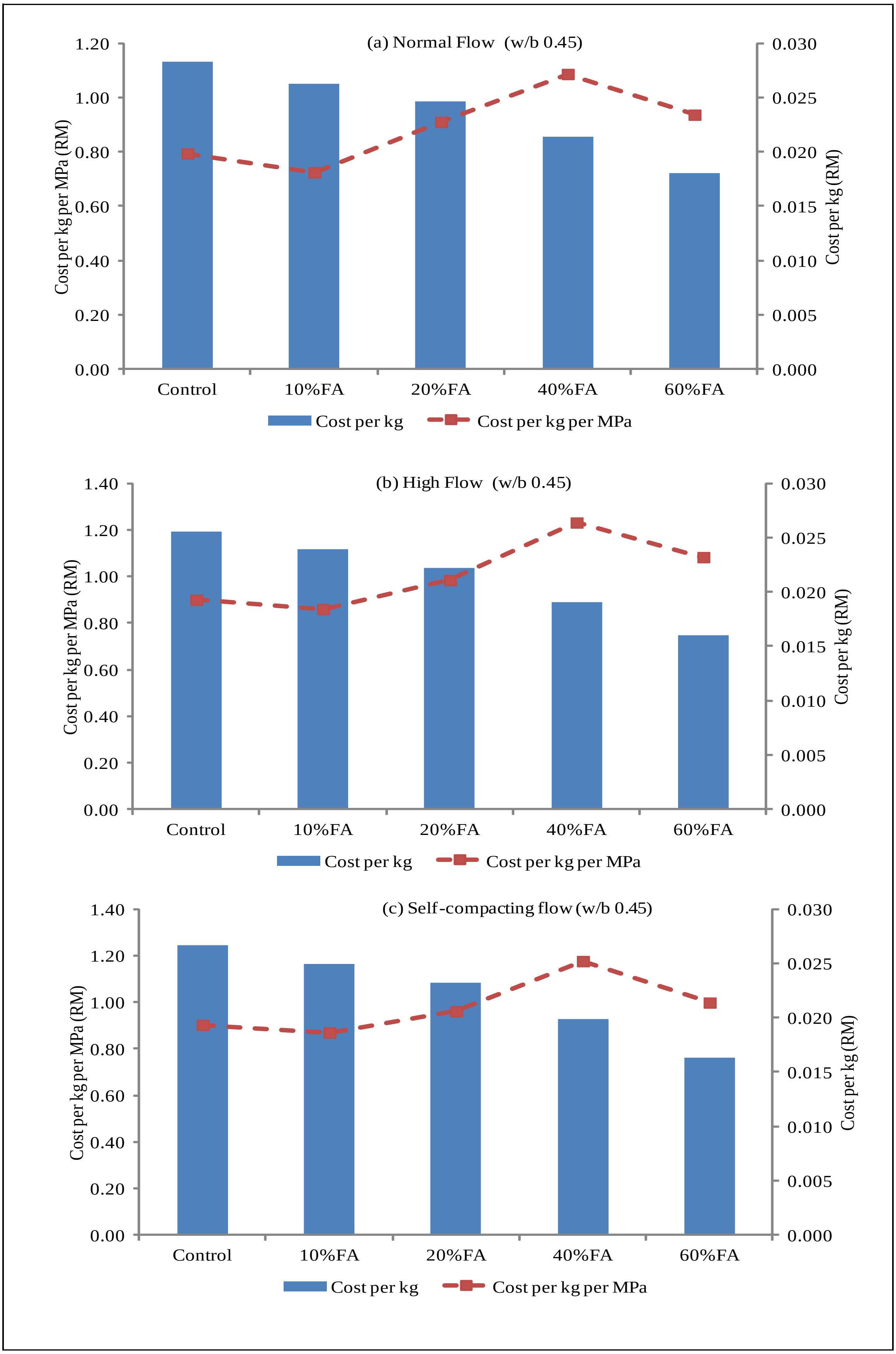


Figure 4.32 Cost-strength w/b 0.45

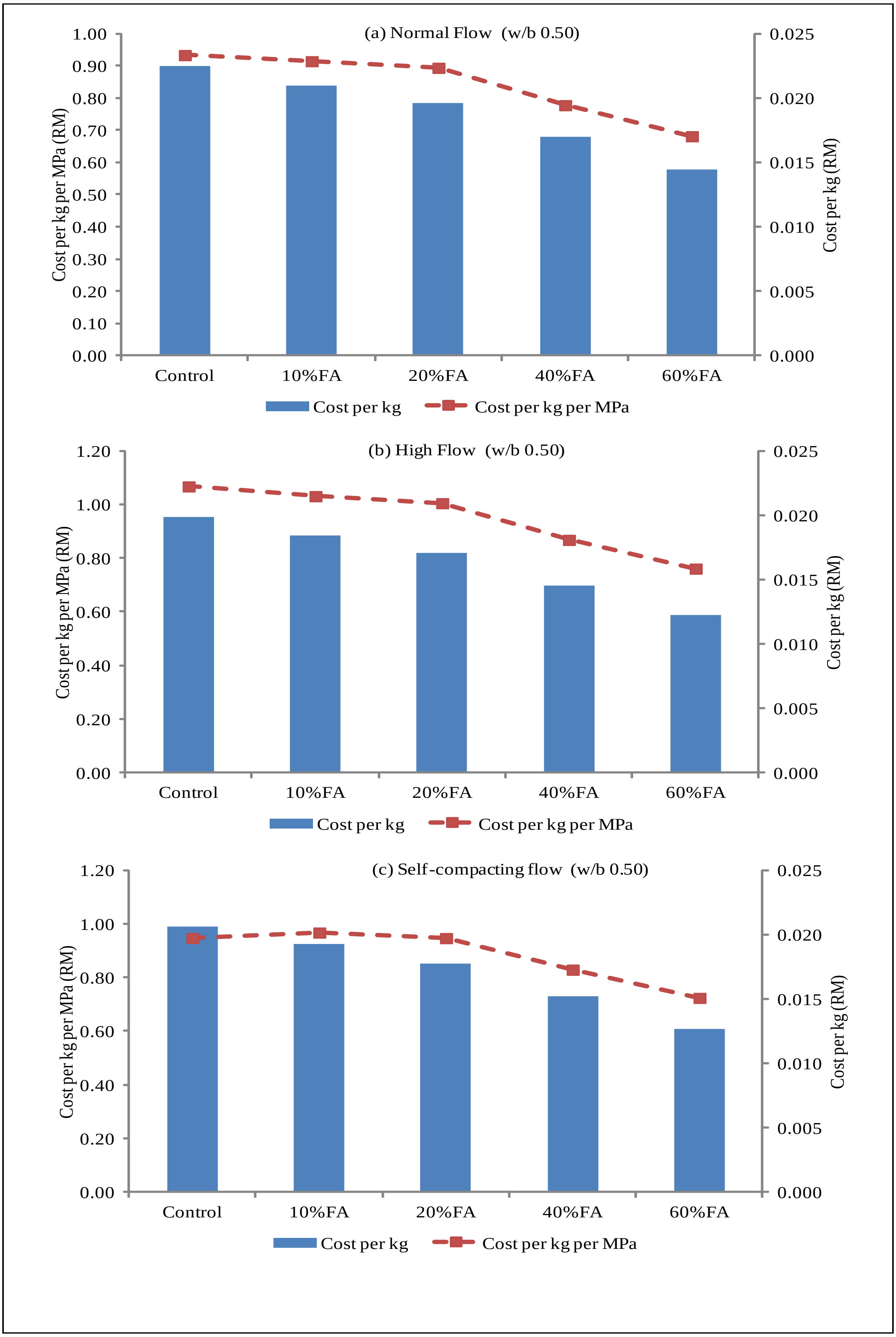


Figure 4.33 Cost-strength w/b 0.50

4.4.2 Cost factor versus environmental sustainability

As the green technology adaptation has become part of the construction industry requirements, assessment on the cost factor and carbon footprints are vital to evaluate the effectiveness of the mortar mixes. Figure 4.34 to Figure 4.37 respectively shows the cost comparison for cost per kg per CO_2 footprint of mortar mixes and cost per kg of mortar. The relationship specifically shows the three types of mortar with different workability requirements. The results of the assessment will shed light on the potential for reduction in greenhouse gas emissions and the possibility of reducing cost.

A linear trend was obtained through the analysis between cost factor and sustainability requirement for all w/b ratios and type of flows. It was found that with decrease in cost per unit of weight consequently will increase the cost per unit of CO_2 footprint. The additional usage of SP for each self-compacting mix elevated the cost per unit of weight especially for low w/b ratio mixes.

Comparing the cost per unit of CO_2 footprint for each w/b ratio, there was a marginal difference between all them particularly for control mixes and mixes with 10% and 20% fly ash replacements. A significant rise in cost per unit of CO_2 footprint was observed when fly ash replacement level was increased to 40% and 60%. It can be deduced that at higher substitution level, the carbon impact can be lowered. Besides that, the variation in cost per unit of weight and cost per unit of CO_2 footprint also showed lowest variation at higher w/b ratio 0.50. However, it should be taken into account that, while maintaining the environmental performance, measures must be taken also to ensure a good balance between the engineering properties and environmental sustainability criteria.

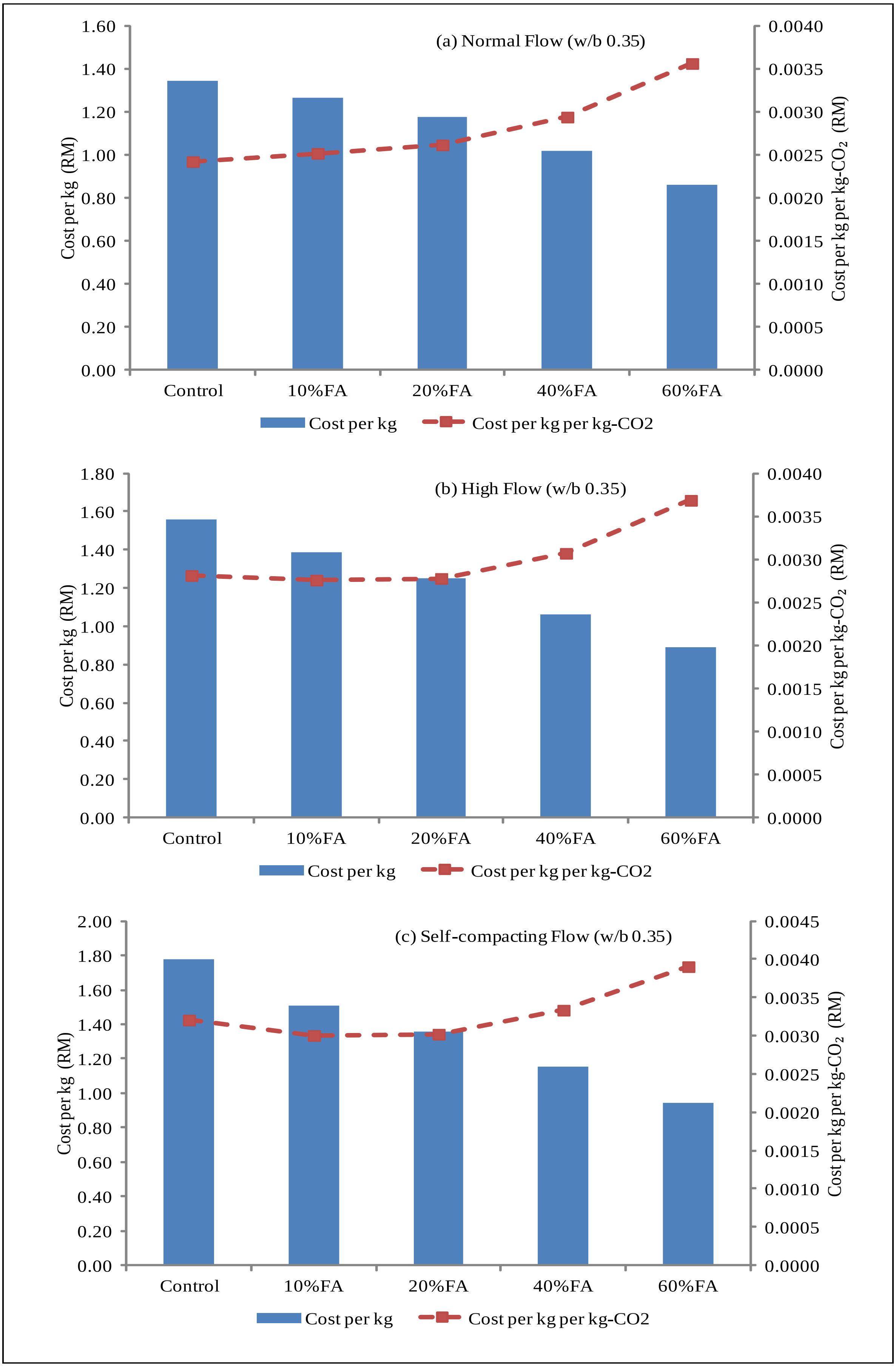


Figure 4.34 Cost-CO_2 footprint w/b 0.35

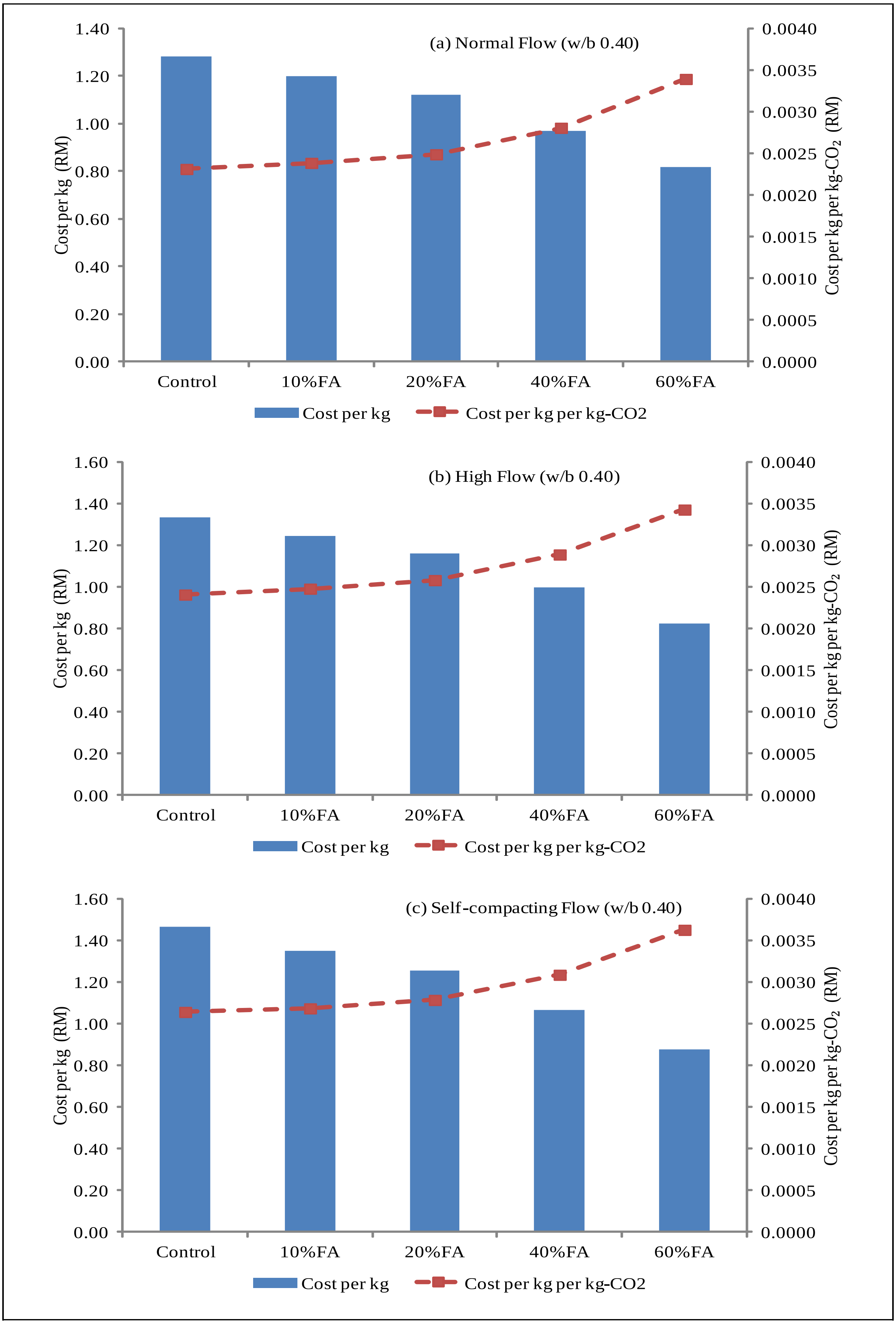


Figure 4.35 Cost-CO_2 footprint w/b 0.40

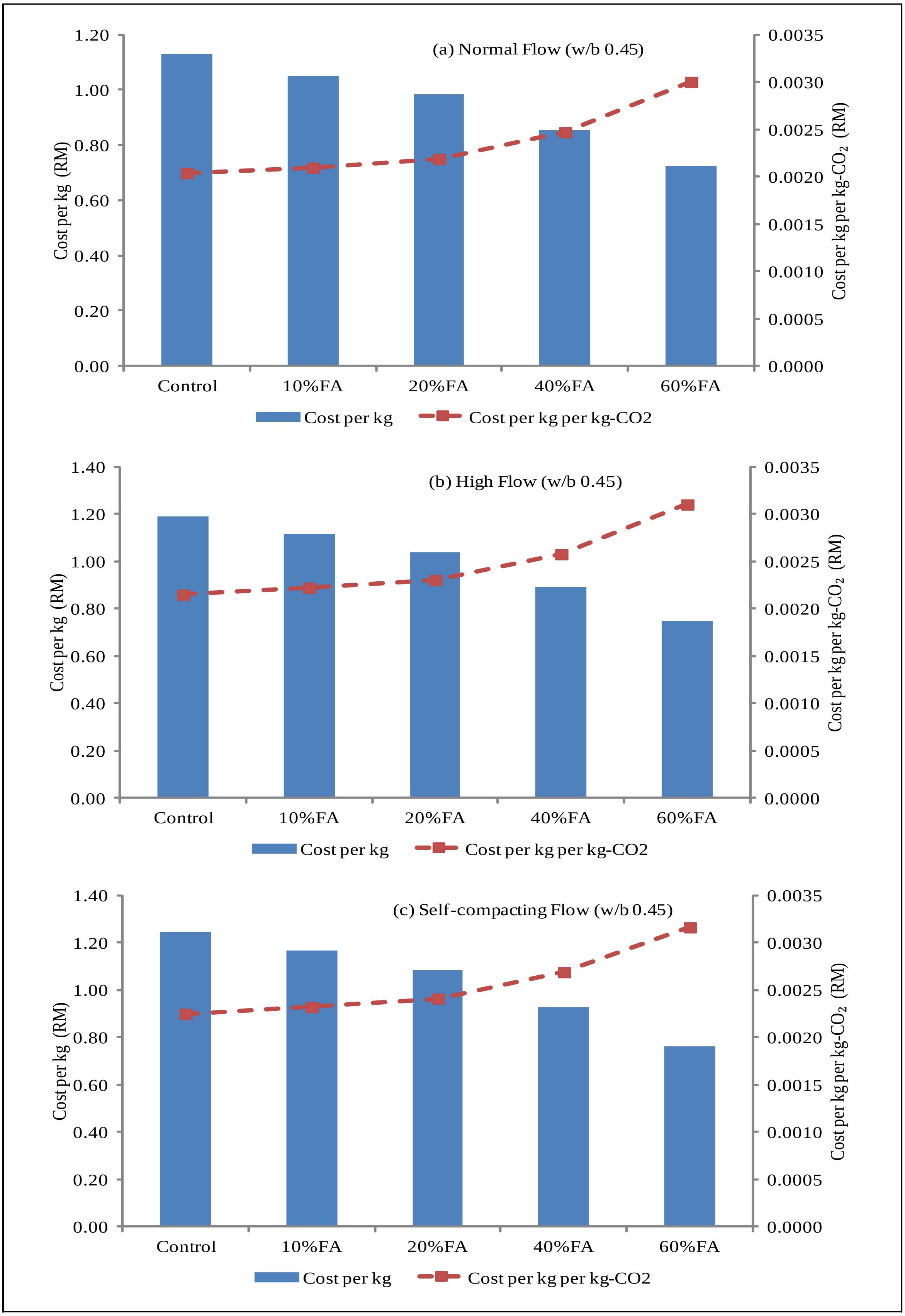


Figure 4.36 Cost-CO_2 footprint w/b 0.45

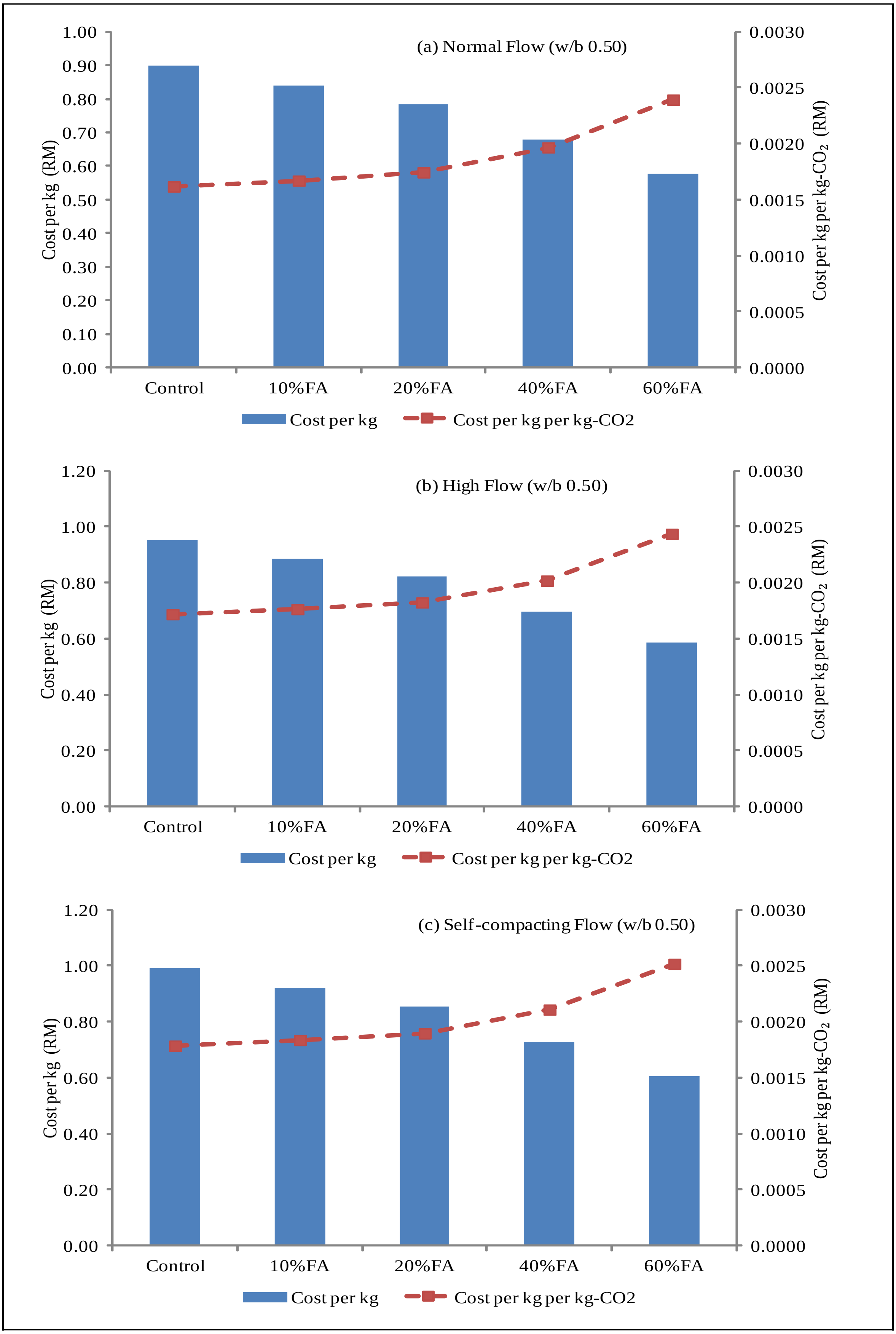


Figure 4.37 Cost-CO_2 footprint w/b 0.50

4.5 Optimum Mixes

Evaluation of the optimum mix was determined based on the relationship among the compressive strength at 28 days, water absorption and the CO_2 footprint. The intersection point between the CO_2 footprint and both the compressive strength and water absorption is suggested as the optimum mix.

4.5.1 Optimum mix based on environmental sustainability and compressive strength

Figure 4.38 to Figure 4.41 show the evaluation for the optimum mix based on the environmental sustainability and compressive strength for w/b ratios of 0.35, 0.40. 0.45 and 0.50.

Based on Figure 4.38 for w/b ratio 0.35, it can be deduced that the intersection point between the CO_2 footprint and compressive strength for normal and self-compacting flow lies at 10% replacement with fly ash. However, for high flow mixes, the intersection falls on the control mixes. It is clearly observed from all the figures for w/b ratio 0.40, that the optimum mixes were at 10% fly ash replacement. Meanwhile, the mixes with w/b ratio 0.45 produced an optimum mix at the 20% fly ash replacement level for all the flow mixes. In addition, for w/b ratio 0.50, for normal and self-compacting flow, the optimum level was gained at 20% fly ash replacement, while for the high flow mixes, an optimum mix was found at 10% fly ash.

The analysis carried out on the optimum mix based on the CO_2 footprint and compressive strength showed that 50% of the overall flow mixes indicated an optimum mix at the 10% replacement level of fly ash over the total mixes. However, 41.7% of the flow mixes indicated that 20% of fly ash replacement is optimum, while the control mix covered the remaining 8.7%. This suggests that the optimum replacement level for fly ash considering the CO_2 footprint and strength enhancement is at 10%.

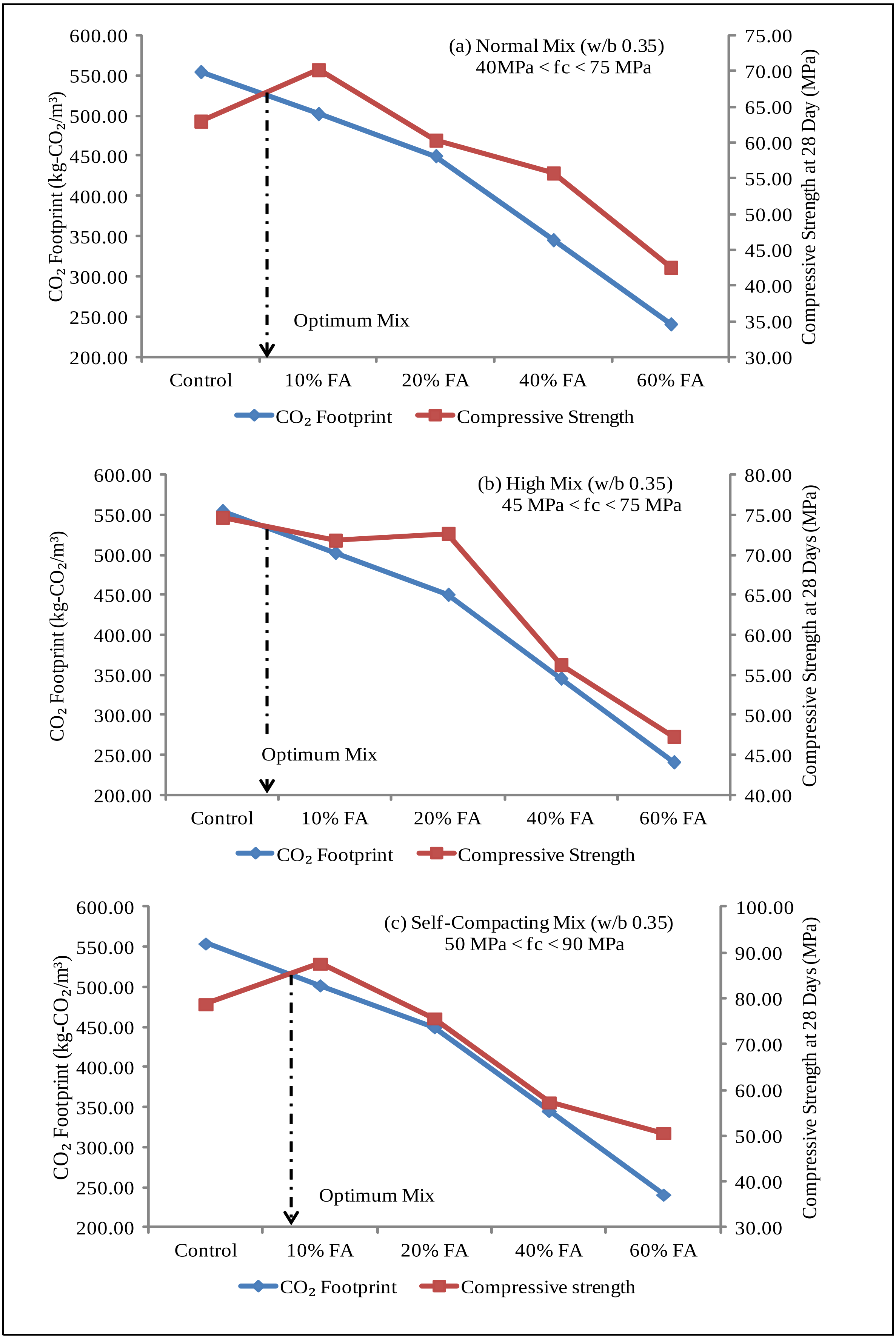


Figure 4.38 Optimum mix based to compressive strength w/b 0.35

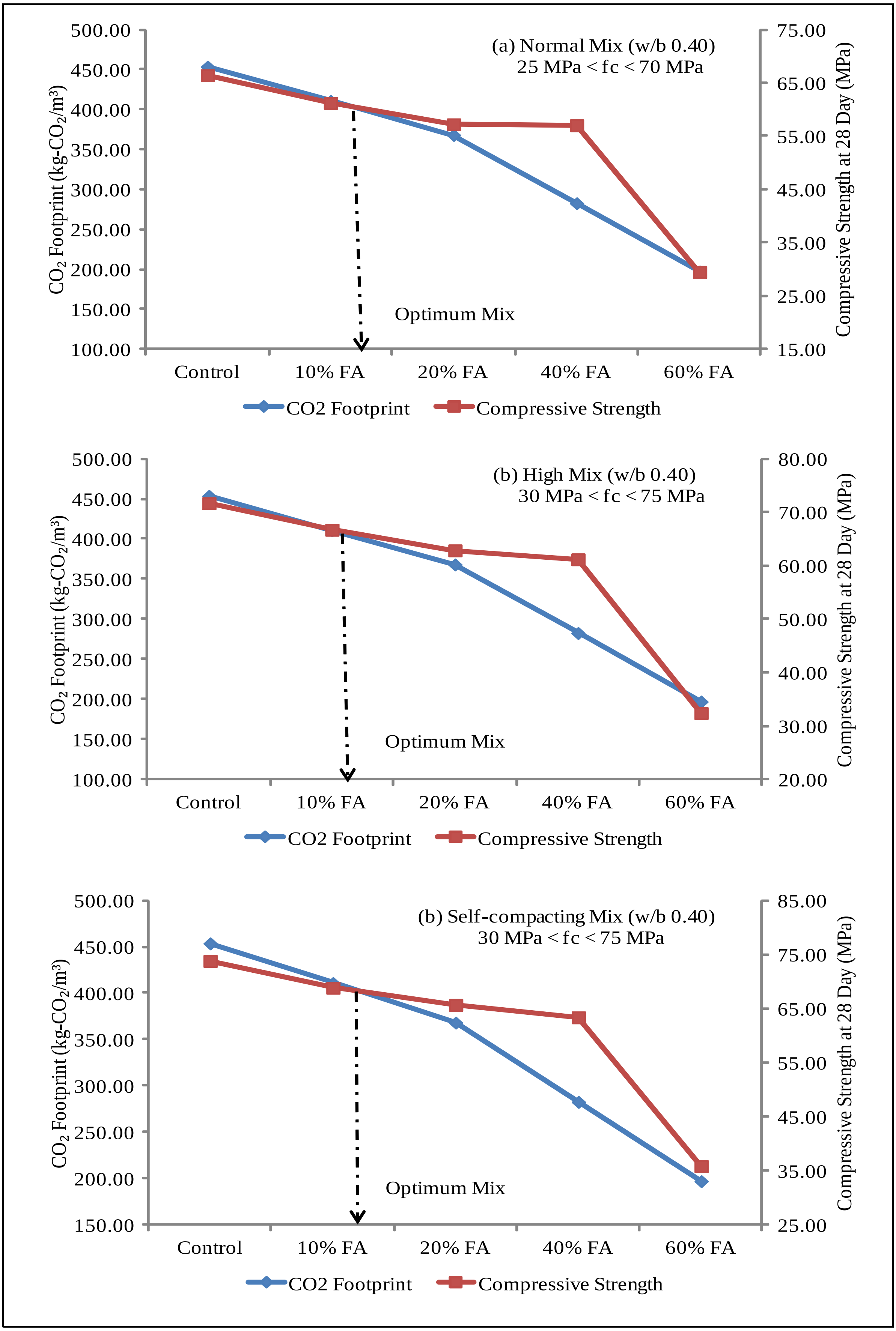


Figure 4.39 Optimum mix based to compressive strength w/b 0.40

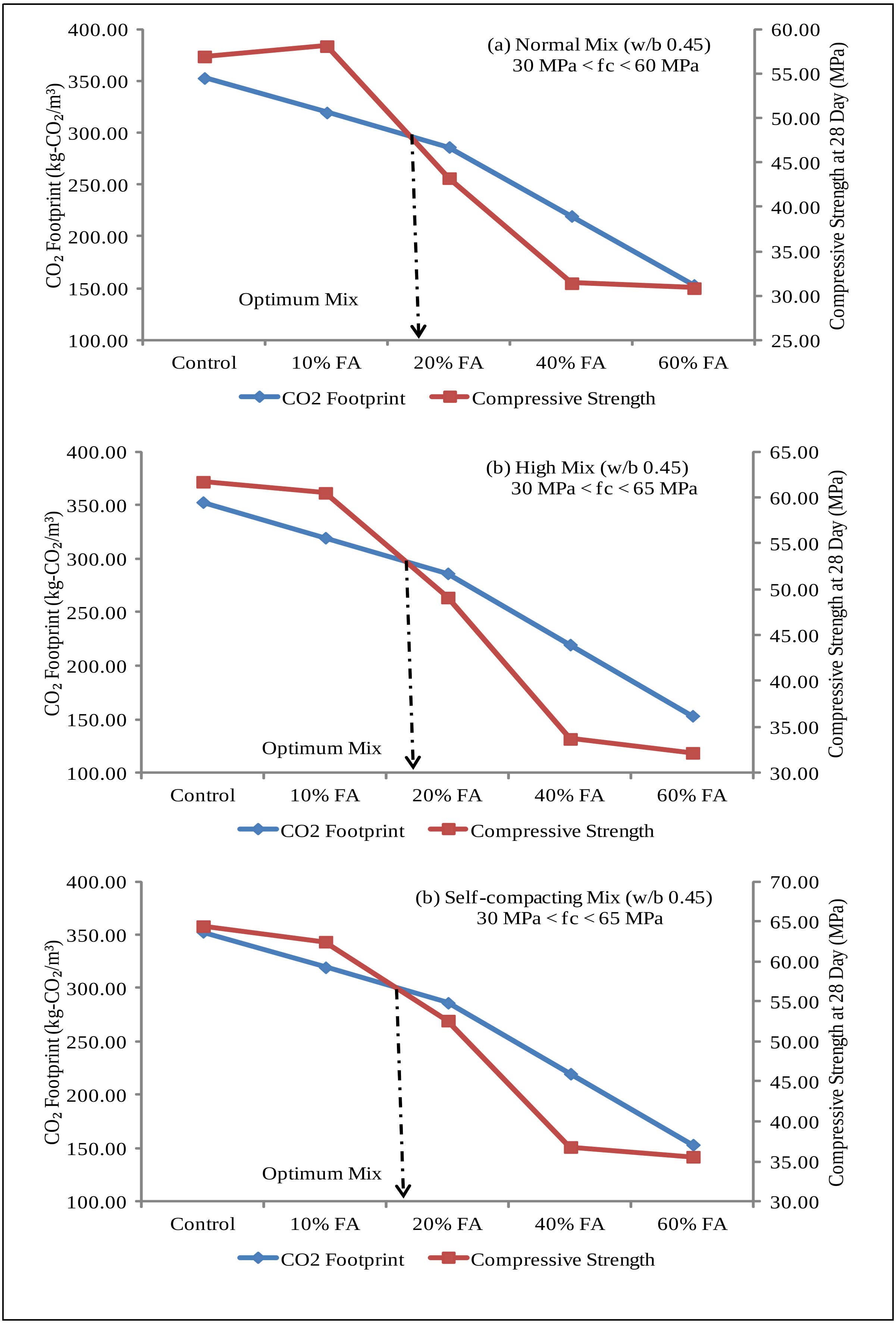


Figure 4.40 Optimum mix based to compressive strength w/b 0.45

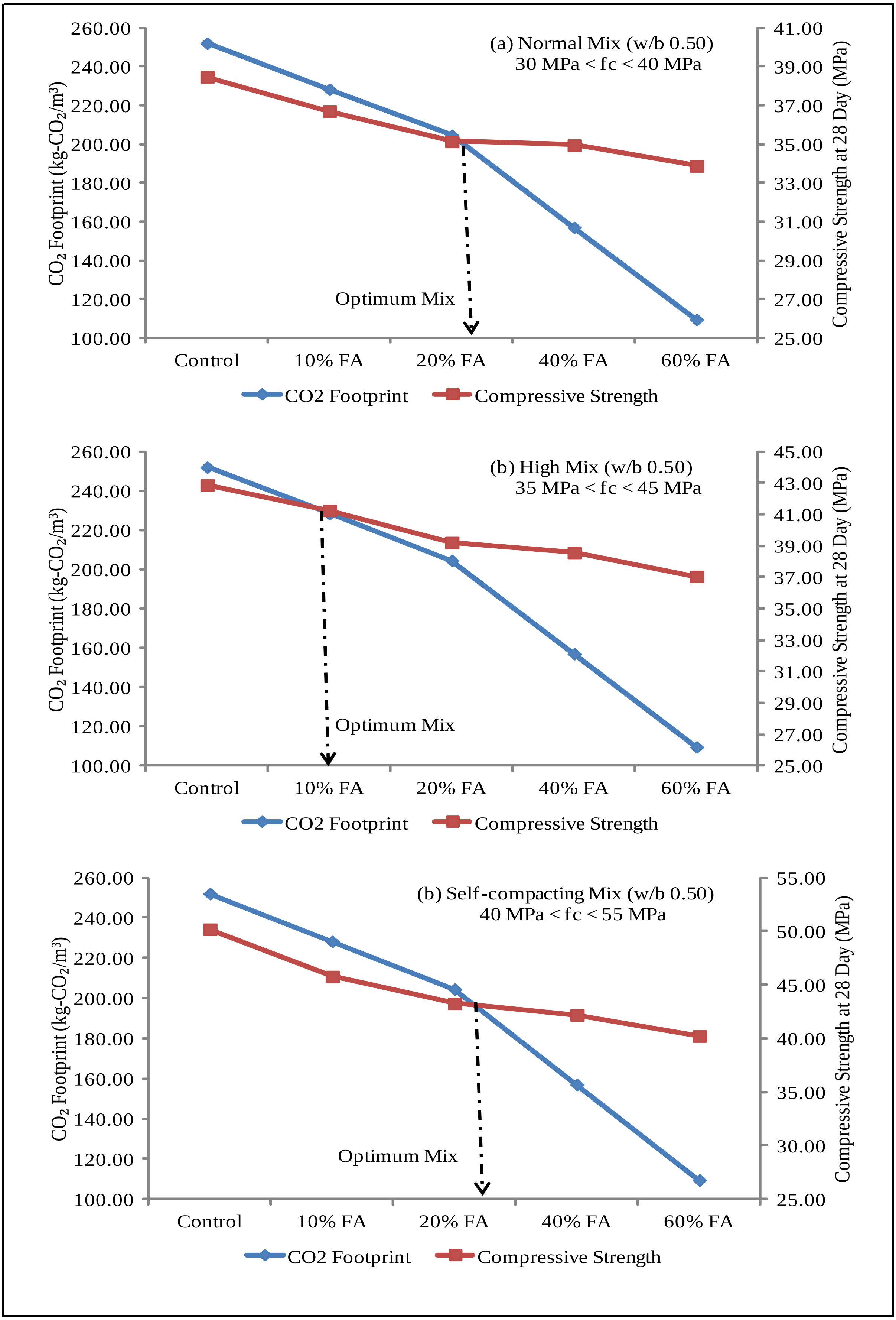


Figure 4.41 Optimum mix based to compressive strength w/b 0.50

4.5.2 Optimum mix based on environmental sustainability and durability

While comparing the optimum mix based on the CO_2 footprint and water absorption, as illustrated in Figure 4.42 to Figure 4.45, the 20% replacement of fly ash emerged as the optimum mix for all self-compacting flow mixes for all w/b ratios. However, it appears that at w/b ratio 0.35 for high flow mixes the optimum mix is 10% fly ash replacement. A similar observation was made for the higher w/b ratio of 0.50 whereby 10% fly ash replacement produced the optimum mix for normal and high flow. The remaining flow mixes showed the optimum mix for 20% fly ash replacement.

As illustrated in Figure 4.42 to Figure 4.45, 20% fly ash replacement dominated as the optimum mix, especially for the w/b ratios of 0.40 and 0.45, for all types of flow mix. The analysis of the optimum mix based on durability and environmental sustainability found that at 20% fly ash replacement dominates by 75% as the optimum mix of total flow mixes whereby 10% fly ash replacement indicates the remaining 25%. From the analysis, the optimum replacement level for fly ash considering the environmental sustainability (CO_2 footprint) and durability performance (water absorption) is at 20% fly ash replacement.

From the complete analysis carried out, it was found that the optimum values for both the CO_2 footprint and water absorption eventually produced an optimum value of water absorption with a low CO_2 footprint. At the 20% fly ash replacement level, an optimum rate of absorption and CO_2 footprint was observed, which is more effective for self-compacting mortar.

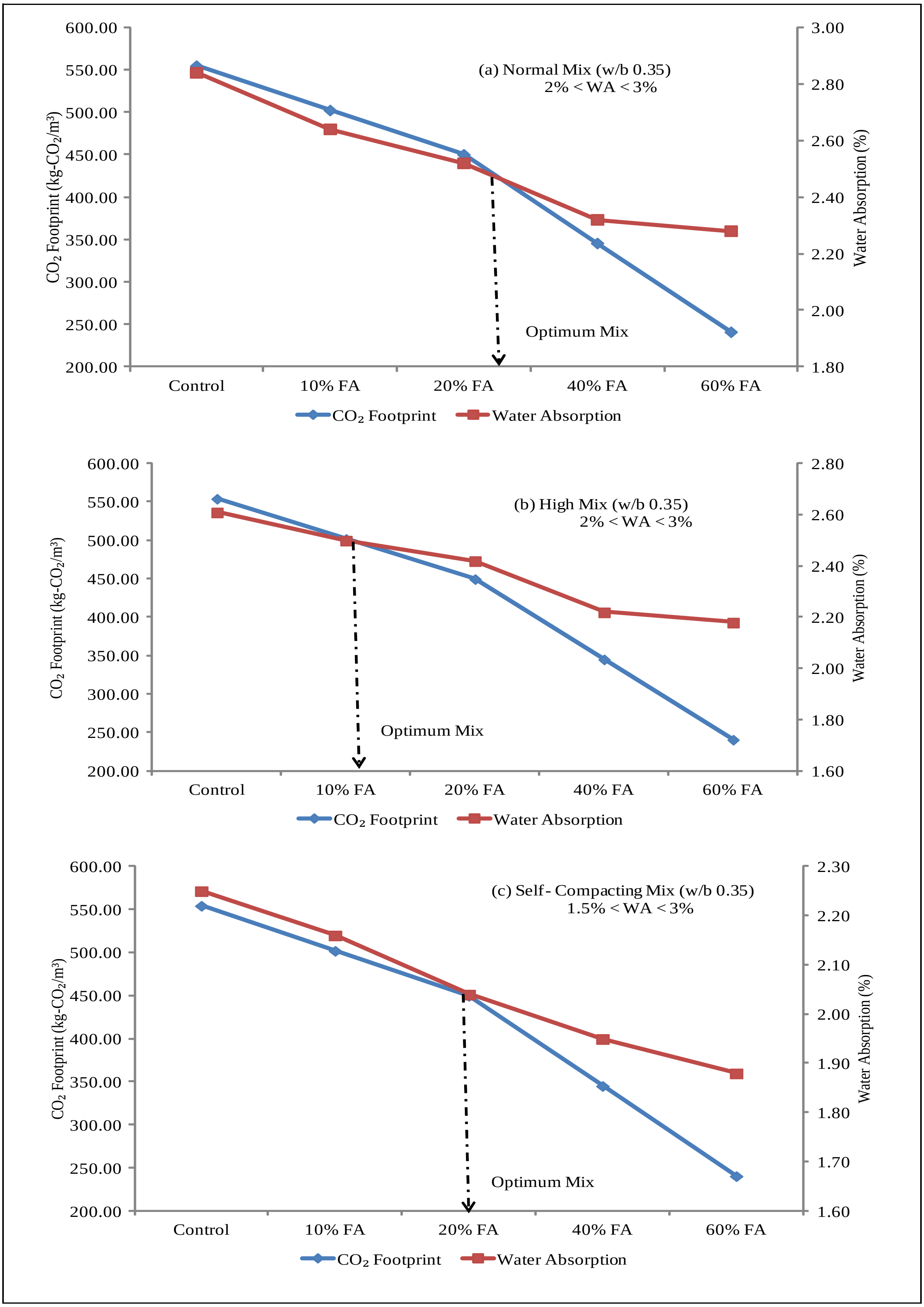


Figure 4.42 Optimum mix based to water absorption w/b 0.35

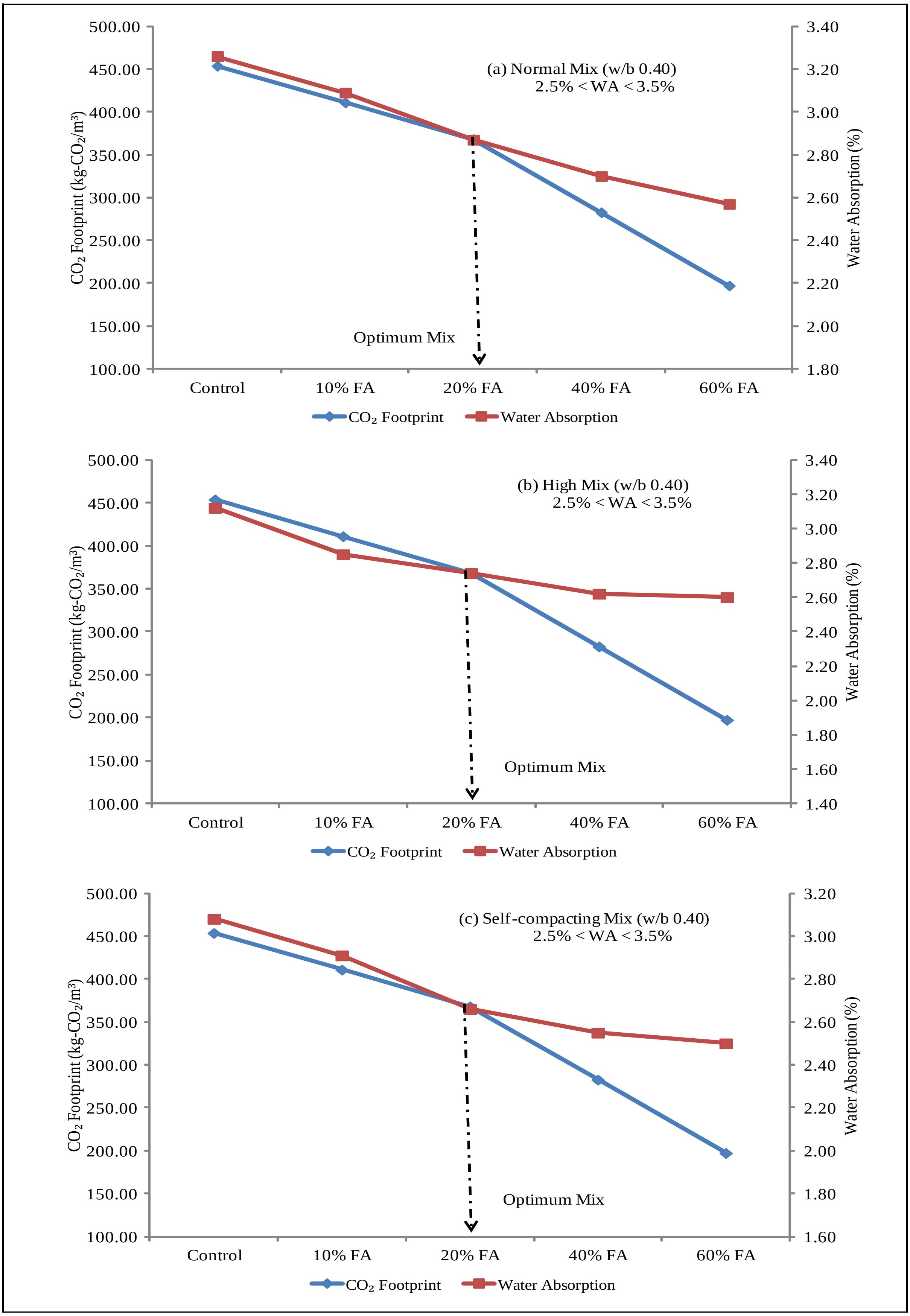


Figure 4.43 Optimum mix based to water absorption w/b 0.40

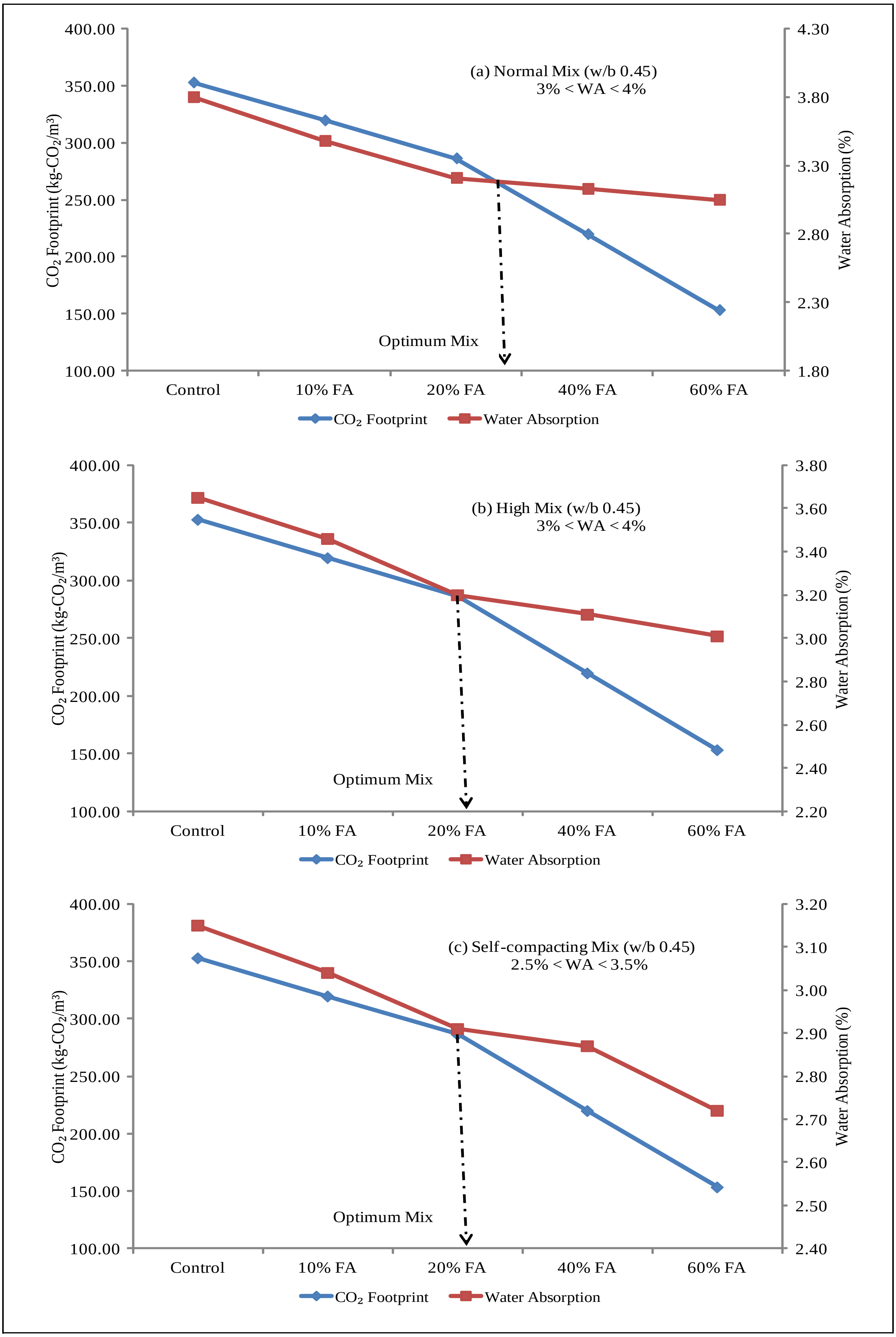


Figure 4.44 Optimum mix based to water absorption w/b 0.45

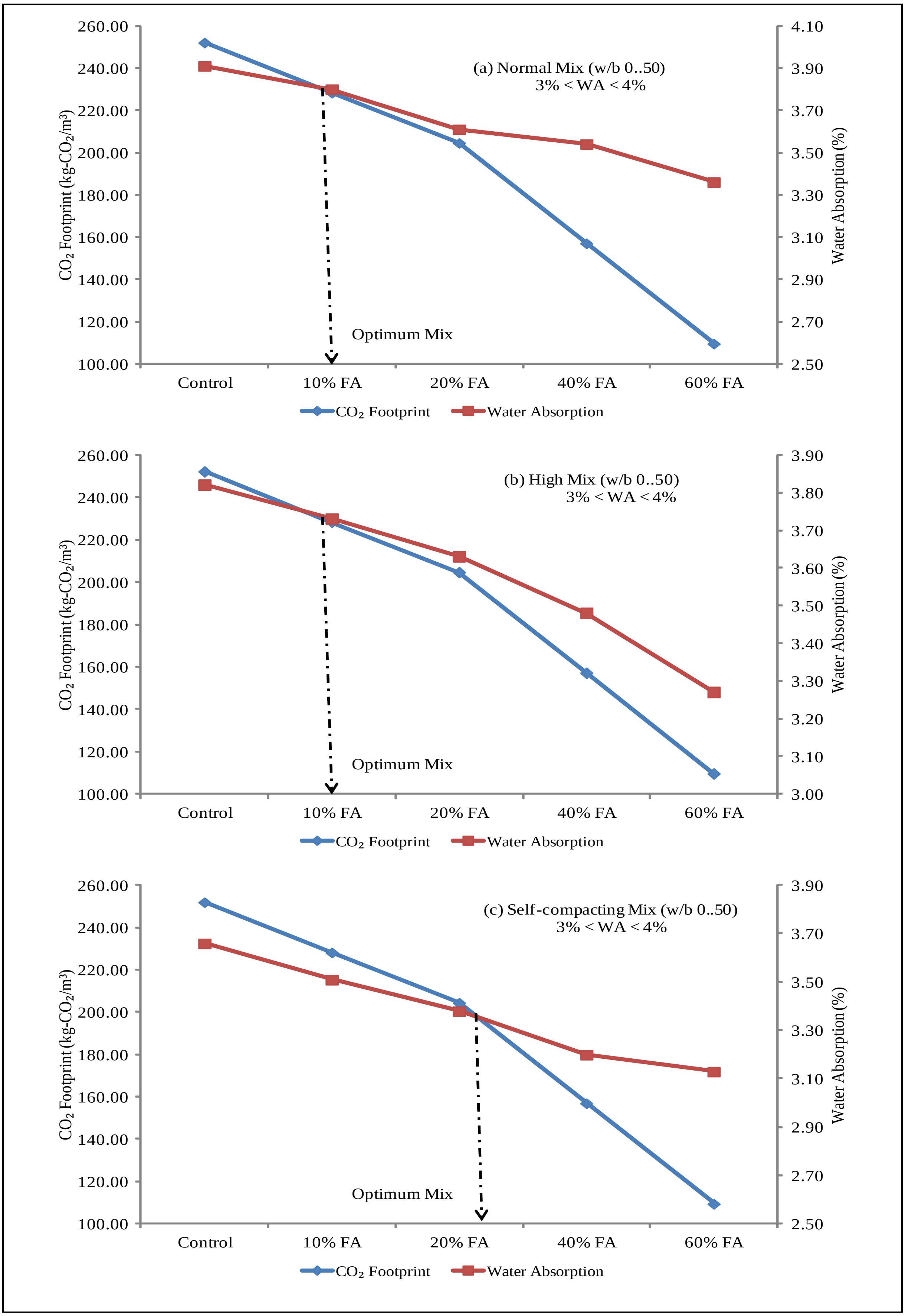


Figure 4.45 Optimum mix based to water absorption w/b 0.50

4.6 Conclusion

Analysis of this research revealed that for targeted spread flow value, the dosages of superplasticizer (SP) used in mortars reduced with the replacement level of fly ash thus creating a reduction of cost in producing the mortar mixture. Simultaneously, the flowability of the mixes improves with the incorporation of fly ash. SP dosage is playing its role as dependent variable in order to achieve targeted workability which is normal, high and self-compacting flow. Hence, it can be concluded that the SP dosage utilized is highly dependent on the percentage of fly ash replacement level and workability. By increasing the fly ash replacement level, it will result in a better workability especially for normal mixes. It was observed from analysis of the effects of fly ash in slump flow that increasing the fly ash level will enhanced the workability although a lower SP dosage was required to achieve the targeted slump.

The relationship of fly ash replacement to mini V-funnel flow was observed that with the addition of fly ash at every replacement levels 10%, 20%, 40% and 60% respectively, a proportionate reduction with the V-funnel time occurred. Durability assessment found that self-compacting mixes observed have low ranges at 1.5 % < WA < 2.5 % of absorption compared to other w/b. These shows that self-compacting mix at lower w/b ratio is more durable compared to high w/b ratio. Similar findings was reported by (Siddique, 2013) that all SCC mixes had low absorption characteristic (less than 10%).

Analysis of compressive strength observed that there was a significant gain in compressive strength due to introduction of mineral admixture. Generally, at normal flow mixes, only 10% and 20% fly ash replacement produced early strength enhancement, with 10% fly ash achieving a higher relative strength from 3 days onwards. Nevertheless, the strength continued to show an increment whereby at 10%, 20%, 40% there was an enhancement of strength at the later age of 90 days. The high flow mixes and self-compacting flow mixes did not produce an early strength enhancement, which may be due to the filler effect and acceleration process of cement hydration. Instead, a decrease in the compressive strength at the early ages was observed in which the reduction was proportional to the replacement level.

The relationship between environmental sustainability and engineering performance shows that with respect to the compressive strength, a direct relationship was found between the 28 day compressive strength and CO_2 footprint. Lower CO_2 footprint showed lower strength of achievement and vice versa. Interestingly, self-compacting flow seems to give better strength yet with a low CO_2 footprint. Observation for durability aspect shows that the dominant factor in determining the relationship between durability and environmental sustainability is highly dependent on the w/b ratio rather than the type of flow. Low w/b ratio seems to provide better performance in terms of durability as it will have fewer pores specifically with the addition of minerals admixture. Hence, from the analysis carried out it can be concluded that self-compacting flow gave the lowest water absorption with lowest CO_2 footprint.

Similar observation was captured while comparing relative performance index of engineering performance to the environmental performance. It was observed that mixes with replacement of 10% to 20% fly ash gave the better results of relative performance index where requires only 6% to 8% in achieving the index 1.0. Cost factor analysis found that control mixes for any type of flow indicate significantly high cost per kg of mortar. Besides that, a linear trend was also obtained throughout the w/b 0.35 mixes with a proportionate decrease in cost per kg of mortar while replacing with mineral admixtures. It was also found that with decrease in cost per unit of weight consequently will increase the cost per unit of CO_2 footprint. Optimum replacement level for fly ash considering the CO_2 footprint and strength enhancement is at 10%, while the optimum replacement level for fly ash considering the environmental sustainability (CO_2 footprint) and durability performance (water absorption) is at 20% fly ash replacement. This suggest that 10% to 20% replacement of fly ash is the optimum replacement in balancing both environmental performance and engineering performance.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.0 Introduction

This research has been entirely focused on evaluating and determining relationship established between engineering performances and environmental sustainability impact of mortar flow mixes. This chapter is intended to give an overall review of this study. The aim and objectives of this study which have been established earlier would be confirmed in this chapter by reviewing the information gathered through the literature review and findings captured in chapter four. Nevertheless, there are some recommendations offered to readers for further research.

5.1 Conclusion

Environmental sustainability performance was correlated with engineering properties of mortar in three different spread flows (normal, high and self-compacting). The experimental results clearly demonstrate that replacing cement with other materials can reduce the environmental impact by reducing the CO_2 footprint. From this study, it was found that for targeted spread flow value, the dosages of superplasticizer (SP) used in mortars reduced with the replacement level of fly ash thus creating a reduction of cost in producing the mortar mixture. It can be deduced that percentage of SP dosage is dependent on percentage of fly ash and also workability level. By increasing of fly ash replacement level it will result on better workability, especially for normal mixes.

Addition of fly ash at every replacement levels 10%, 20%, 40% and 60% is proportionate in reducing the V-funnel time. While comparing slump flow (Γ_m) against relative funnel time speed (R_m) indicate that results obtained are mostly within the limits set by (EFNARC, 2002).

Durability assessment was deduced by water absorption test. Analysis found that addition of fly ash appeared to reduce the water absorption and elevate the durability performance of the mortar samples. Analysis also found that self-compacting mix at lower w/b ratio is more durable compared to high w/b ratio.

A significant observation was encountered for compressive strength analysis whereby at 10% fly ash replacement achieves higher compressive strength than the control mixture from 3 days onwards. This may due to filler effect present at this low w/b ratio with low fly ash replacements. Generally, at normal mixes, only 10% and 20% fly ash replacement produce early strength enhancement. Relative strength plots found that an immediate dilution effect occurred whereby the early strength could be reduced in approximate proportion to the degree of replacement.

Linearity of the plots for CO_2 footprint analysis shows that the reduction of CO_2 footprint is proportionate with reduction of w/b ratio and amount of fly ash replacement. Analysis also revealed that by replacing fly ash to maximum level i.e. 60%, will provide the best CO_2 footprint reduction with a decrease of more than 50% CO_2 footprint compared to other mixes.

In evaluating the relationship between engineering properties and environmental sustainability, analysis of strength to environmental sustainability found that with the increase in strength, a linear relationship was obtained between 28 days strength and CO_2 footprint. Lower CO_2 footprint showed lower strength achievement and vice versa. Interestingly, analysis revealed that self-compacting flow mixes seem to give better strength yet with a low CO_2 footprint. Analysis of durability to environmental sustainability concluded that self-compacting flow gave the lowest water absorption with lowest CO_2 footprint.

Best environmental-mechanical performances are achieved when the performance index is the lowest. Analysis of relative performance index for mechanical performances and CO_2 footprint found at higher w/b ratio of 60% replacement produced the lowest relative performance index with 0.49 which is 50% lesser from OPC mortar.

Cost factor analysis found that the highest cost occurred at w/b ratio 0.35 during control mix of self-compacting flow with RM1.78 per kg of mortar mixes. The lowest cost was obtained when 60% replacement of fly ash at w/b ratio of 0.50 of normal flow with RM0.58 per kg of mortar mixes. Thus it can be concluded that the decrease in cost with introduction of mineral admixtures into the mixes was proportionate for every w/b ratio.

Cost analysis based on cost per unit of weight and cost per unit of strength shows that the cost of each kg of mortar is directly proportional to strength, whereby for higher strength, the cost increase. Cost analysis revealed that, cost per kg of mortar for self-compacting flow is increased by 44% while compare to normal flow. In comparing between the mixture economics of the three type of flowability, it is found that self-compacting flow at less percentage fly ash replacement more favourable since it gave low cost per unit strength specially at low w/b ratio.

Cost analysis based on environmental sustainability found that with decrease in cost per unit of weight consequently will increase the cost per unit of CO_2 footprint. A significant rise in cost per unit of CO_2 footprint was observed when fly ash replacement level was increased to 40% and 60%. It can be deduced that at higher substitution level, the carbon impact can be lowered.

The optimum replacement level for fly ash considering the CO_2 footprint and strength enhancement is at 10% for all the targeted flow mixes. While comparing CO_2 footprint and water absorption at every w/b ratio, it was concluded that 20% of fly ash replacement for self-compacting flow mix is the optimum since it gave the lowest value of rate of absorption and also CO_2 footprint.

In general, this study has demonstrated that with addition of fly ash as mineral admixture, it helps in improving the compressive strength, durability yet giving low CO_2 footprint impact. Utilisation of fly ash also proved that it is a sustainable material since by addition of fly ash up to the maximum level, gives the best performance index level with low cost. However in general it was found that with replacement of 10% to 20% of fly ash gave the optimum replacement since it provided a balance in environmental sustainability performance and mechanical performance.

5.2 Recommendations

Further improvement can be done in the near future in order to ensure the continuity of research in self-compacting concrete or in the field of mortar sustainability. Engineering properties investigated during the hardened state are limited only to compressive strength and durability properties. Various engineering properties may be investigated by future researcher such as other strength properties. The relationship examined is between environmental sustainability and engineering properties in a limited scope. Various relationships may be develop by incorporating more mechanical performance tests in future study.

CO_2 footprint of mortar in this research is derived solely by using inventory data readily available from industries; further research mainly in determining the CO_2 footprint from its sources e.g. transportation, energy sources will probably gather more precise and accurate data of CO_2 footprint in concrete or mortar. Since sustainability has become important nowadays, future researcher may address not only environmental and economic impact but also social impact should be included in future study. Additionally, the significant potential of fly ash as mineral admixture in reducing the CO_2 footprint warrants further research and development. Different mineral admixtures may be adopted in future research such as by using rice hush ash (RHA), ground granulated blast slag (GGBS), silica fume and other waste materials from the local industry.

REFERENCES

Akram, T., Memon, S. A., & Obaid, H. (2009). Production of low cost self compacting concrete using bagasse ash. *Construction and Building Materials, 23*(2), 703–712. doi:10.1016/j.conbuildmat.2008.02.012

Ashley, E. (2008). Concrete Sustainability. *Journal of Green Building*, *1*(4), 2–40. doi:10.3992/jgb.3.4.37

ASTM C618-12a. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use in Concrete. American Society for Testing Materials; 2013.

ASTM C305. Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. American Society for Testing Materials; 2012.

ASTM C109-C109M. Standard Test Method For Compressive Strength Of Hydraulic Cement Mortars (Using 2-In. Or [50-Mm] Cube Specimens. American Society for Testing Materials; 2013.

ASTM C511. Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. American Society for Testing Materials; 2009.

Barbhuiya, S. (2011). Effects of fly ash and dolomite powder on the properties of self-compacting concrete. *Construction and Building Materials*, *25*(8), 3301–3305. doi:10.1016/j.conbuildmat.2011.03.018

Becchio, C., Corgnati, S. P., Kindinis, A., & Pagliolico, S. (2009). Improving environmental sustainability of concrete products: Investigation on MWC thermal and mechanical properties. *Energy and Buildings*, *41*(11), 1127–1134. doi:10.1016/j.enbuild.2009.05.013

Benabed, B., Kadri, E.-H., Azzouz, L., & Kenai, S. (2012). Properties of self-compacting mortar made with various types of sand. *Cement and Concrete Composites*, *34*(10), 1167–1173. doi:10.1016/j.cemconcomp.2012.07.007

Bentz, D. P., Hansen, A. S., & Guynn, J. M. (2011). Optimization of cement and fly ash particle sizes to produce sustainable concretes. *Cement and Concrete Composites*, *33*(8), 824–831. doi:10.1016/j.cemconcomp.2011.04.008

Björk, F. (1999). Concrete Technology and Sustainable Development. In *Key Issues from the 1999 Vancouver Symposium on Concrete Technology for Sustainable Development* (pp. 1–9).

Braga, M., de Brito, J., & Veiga, R. (2012). Incorporation of fine concrete aggregates in mortars. *Construction and Building Materials*, *36*, 960–968. doi:10.1016/j.conbuildmat.2012.06.031

BS 1881-122. Method for Determination Of Water Absorption. British Standard; 2011.

BS 882. Specification for Aggregates from Sources for Concrete (Amendment 1). British Standard; 1992.

BS 410-1. Test Sieves - Technical Requirements and Testing. British Standard; 2000.

Cagiao, J., Gómez, B., Doménech, J. L., Mainar, S. G., & Lanza, H. G. (2011). Calculation of the corporate carbon footprint of the cement industry by the application of MC3 methodology. *Ecological Indicators*, *11*(6), 1526–1540. doi:10.1016/j.ecolind.2011.02.013

Carbon Index. (2008). The Carbon Index (Vol. 8, p. 13).

Carbon Trust, Carbon Trust website, 2009, What is a Carbon Footprint?[Online] [Cited: Nov 25,2011.] http://www.carbontrust.co.uk/solutions/CarbonFootprinting/what_is_a_carbon_footprint .htm.

Cement & Concrete Institute. (2011). *Sustainable Concrete*.

Chau, C. K., Hui, W. K., Ng, W. Y., & Powell, G. (2012). Assessment of CO2 emissions reduction in high-rise concrete office buildings using different material use options. *Resources, Conservation and Recycling*, *61*, 22–34. doi:10.1016/j.resconrec.2012.01.001

Corinaldesi, V., & Moriconi, G. (2011). Characterization of self-compacting concretes prepared with different fibers and mineral additions. *Cement and Concrete Composites*, *33*(5), 596–601. doi:10.1016/j.cemconcomp.2011.03.007

Cyr, M., Trinh, M., Husson, B., & Casaux-Ginestet, G. (2013). Design of eco-efficient grouts intended for soil nailing. *Construction and Building Materials*, *41*, 857–867. doi:10.1016/j.conbuildmat.2012.12.020

Damineli, B. L., Kemeid, F. M., Aguiar, P. S., & John, V. M. (2010). Measuring the eco-efficiency of cement use. *Cement and Concrete Composites*, *32*(8), 555–562. doi:10.1016/j.cemconcomp.2010.07.009

Damtoft, J. S., Lukasik, J., Herfort, D., Sorrentino, D., & Gartner, E. M. (2008). Sustainable development and climate change initiatives. *Cement and Concrete Research*, *38*(2), 115–127. doi:10.1016/j.cemconres.2007.09.008

Dehwah, H. a. F. (2012). Mechanical properties of self-compacting concrete incorporating quarry dust powder, silica fume or fly ash. *Construction and Building Materials*, *26*(1), 547–551. doi:10.1016/j.conbuildmat.2011.06.056

Department of Statistic Malaysia. (2010). Special Release 1 Peninsular Malaysia for Civil Engineering Works.

Dinakar, P., Babu, K. G., & Santhanam, M. (2008). Durability properties of high volume fly ash self compacting concretes. *Cement and Concrete Composites*, *30*(10), 880–886. doi:10.1016/j.cemconcomp.2008.06.011

Edward, V. (2010). Cement and Concrete Institute Concrete Industry Greenhouse Gas Emissions. Northcliff.

EFNARC. Specification and guidelines for self compacting concrete; 2002. p. 29-35 http://www.efnarc.org

Ehrenberg, A., and Geiseler, 1997. Jokologische Eigenschaften von Hochofenzement, Bston-Informationen, 37(4): 51-63. In: Bensted and Barnes, Structure and Performance of Cement, Second Edition, Spon press London and New York, pp: 310-325.

Elsen, J. (2006). Microscopy of historic mortars—a review. *Cement and Concrete Research*, *36*(8), 1416–1424. doi:10.1016/j.cemconres.2005.12.006

Europian Union. (2003). Establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. *Official Journal of the European Union*, 32–46.

Fantilli, A. P., & Chiaia, B. (2013). Eco-mechanical performances of cement-based materials: An application to self-consolidating concrete. *Construction and Building Materials*, *40*, 189–196. doi:10.1016/j.conbuildmat.2012.09.075

Figueiras, H., Nunes, S., Coutinho, J. S., & Figueiras, J. (2009). Combined effect of two sustainable technologies: Self-compacting concrete (SCC) and controlled permeability formwork (CPF). *Construction and Building Materials*, *23*(7), 2518–2526. doi:10.1016/j.conbuildmat.2009.02.035

Flower, D. J. M., & Sanjayan, J. G. (2007). Green house gas emissions due to concrete manufacture. *The International Journal of Life Cycle Assessment*, *12*(5), 282–288. doi:10.1065/lca2007.05.327

Gebler, S.H., Klieger, P. (1986): Effect of Fly Ash on the Durability of Air-Entrained Concrete. Preprinted from Proceedings, Second International Conference on the Use of Fly Ash, Silica Fume, Slag, and Other Mineral By-Products in Concrete. April 21-25, 1986, Madrid.

Gesoğlu, M., Güneyisi, E., Kocabağ, M. E., Bayram, V., & Mermerdaş, K. (2012). Fresh and hardened characteristics of self compacting concretes made with combined use of marble powder, limestone filler, and fly ash. *Construction and Building Materials*, *37*, 160–170. doi:10.1016/j.conbuildmat.2012.07.092

Habert, G., & Roussel, N. (2009). Study of two concrete mix-design strategies to reach carbon mitigation objectives. *Cement and Concrete Composites*, *31*(6), 397–402. doi:10.1016/j.cemconcomp.2009.04.001

Halstead, WJ (1986). Used of Fly Ash in Concrete. Highway Research Board, Division of Engineering, National Research Council, National Academy of Engineering, National Academy of Sciences 1969.

Henry, M., & Kato, Y. (2012). Understanding the regional context of sustainable concrete in Asia: Case studies in Thailand and Korea. *Resources, Conservation and Recycling*, *69,* 122–129. doi:10.1016/j.resconrec.2012.09.016

Henry, M., Pardo, G., Nishimura, T., & Kato, Y. (2011). Balancing durability and environmental impact in concrete combining low-grade recycled aggregates and mineral admixtures. *"Resources, Conservation & Recycling"*, *55*(11), 1060–1069. doi:10.1016/j.resconrec.2011.05.020

http://www.sustainableconcrete.org.nz/page/economic-impact.aspx (24/5/2013)

http://www.businessdictionary.com/definition/economic-sustainability.html#ixzz2UDpFtU3Q (24/5/2013)

Illston J.M., Domone, P.L.J. (2001): Construction Materials, Their nature and behaviour. Taylor & Francis e-Library, New York, 554 pp.

Izquierdo, M., & Querol, X. (2012). Leaching behaviour of elements from coal combustion fly ash: An overview. *International Journal of Coal Geology*, *94*, 54–66. doi:10.1016/j.coal.2011.10.006

Kamar, K. a. M., & Hamid, Z. a. (2011). Sustainable construction and green building: the case of Malaysia. *Sustainability Today*, 15–22. doi:10.2495/ST110021

Karim, M. R., Zain, M. F. M., Jamil, M., Lai, F. C., & Islam, M. N. (2011). Necessity and Opportunity of Sustainable Concrete from Malaysia ' s Waste Materials. *Australian Journal of Basic and Applied Sciences*, *5*(5), 998–1006.

Kayali, O., & Sharfuddin Ahmed, M. (2013). Assessment of high volume replacement fly ash concrete – Concept of performance index. *Construction and Building Materials*, *39*, 71–76. doi:10.1016/j.conbuildmat.2012.05.009

Khaleel, O. R., & Abdul Razak, H. (2012). The effect of powder type on the setting time and self compactability of mortar. *Construction and Building Materials*, *36*, 20–26. doi:10.1016/j.conbuildmat.2012.04.079

Khalfan, M. M. A. (2002). Sustainable Development and Sustainable Construction. *WP/2001/1*, 1–45.

Khatib, J. M. (2008). Performance of self-compacting concrete containing fly ash. *Construction and Building Materials*, *22*(9), 1963–1971. doi:10.1016/j.conbuildmat.2007.07.011

Kim, H. K., Jeon, J. H., & Lee, H. K. (2012). Flow, water absorption, and mechanical characteristics of normal- and high-strength mortar incorporating fine bottom ash aggregates. *Construction and Building Materials*, *26*(1), 249–256. doi:10.1016/j.conbuildmat.2011.06.019

Lange F., Mortel, H., and Rudert, V. (1997). Dense packing of cement pastes and resulting consequences on mortar properties. *Cement and Concrete Research*, *27*, 1481–1488.

Liu, T.C. and Jenn C.C. (2008). Sustainable Concrete Technology for the 21st Century. The 3rd ACF International Conference - ACF/VCA 2008, D.23.

Lund P. Impacts of EU carbon emission trade directive on energy-intensive industries - indicative micro-economic analyses. Ecol Econ 2007;63:799-806.

Malhotra, V.M. & Ramezanianpour, A.A. (1994). Fly Ash in Concrete. Ontario, Canada. The Canada Centre for Mineral and Energy Technology (CANMET).

McLellan, B. C., Williams, R. P., Lay, J., van Riessen, A., & Corder, G. D. (2011). Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of Cleaner Production*, *19*(9-10), 1080–1090. doi:10.1016/j.jclepro.2011.02.010

Meyer, C. (2009). The greening of the concrete industry. *Cement and Concrete Composites*, *31*(8), 601–605. doi:10.1016/j.cemconcomp.2008.12.010

Moldan, B., Janoušková, S., & Hák, T. (2012). How to understand and measure environmental sustainability: Indicators and targets. *Ecological Indicators*, *17*, 4–13. doi:10.1016/j.ecolind.2011.04.033

Neville AM, Brooks JJ. Concrete technology. Longman; 1987

N.Bouzoubaa,Lachemi, M. (2001). Self-compacting concrete incorporating high volumes of class F fly ash Preliminary results. *Cement and Concrete Research*, *31*, 413–420.

Ng, S. T., Chen, Y., & Wong, J. M. W. (2013). Variability of building environmental assessment tools on evaluating carbon emissions. *Environmental Impact Assessment Review*, *38*, 131–141. doi:10.1016/j.eiar.2012.07.003

Ozawa K, Maekawa K, Okamura H. High Performance concrete with high filling ability. In : Proceedings of the RILEM symposium, admixtures for concrete, Barcelona; 1990.

Parkin, S. (2000), Context and drivers for operationalizing sustainable development, Proceedings of ICE, Vol. 138, Nov. 2000, pp. 9 – 15.

Peris Mora, E. (2007). Life cycle, sustainability and the transcendent quality of building materials. *Building and Environment*, *42*(3), 1329–1334. doi:10.1016/j.buildenv.2005.11.004

Poston R W, Kesner K, McDonald J E, Vaysburd A M, Emmons P H 2001 Concrete repair material performance-Laboratory study. ACI Materials J. 98(2): 137–147

Proske, T., Hainer, S., Rezvani, M., & Graubner, C.-A. (2013). Eco-friendly concretes with reduced water and cement contents — Mix design principles and laboratory tests. *Cement and Concrete Research*, *51*, 38–46. doi:10.1016/j.cemconres.2013.04.011

Raharjo, D., & Subakti, a. (2013). Mixed Concrete Optimization using Fly Ash, Silica Fume and Iron Slag on the SCC's Compressive Strength. *Procedia Engineering*, *54*, 827–839. doi:10.1016/j.proeng.2013.03.076

Ramachandran, V.S., (1995) Concrete Admixture Handbook,doi:http://dx.doi.org/10.1016/B978-081551373-5.50001-5

Rocktron International (2010). "International Greentech & Eco Products Exhibition & Conference Malaysia". www.rktron.com.my

Rodrigues, F. a., & Joekes, I. (2010). Cement industry: sustainability, challenges and perspectives. *Environmental Chemistry Letters*, *9*(2), 151–166. doi:10.1007/s10311-010-0302-2

Sabet, F. A., Libre, N. A., & Shekarchi, M. (2013). Mechanical and durability properties of self consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash. *Construction and Building Materials*, *44*, 175–184. doi:10.1016/j.conbuildmat.2013.02.069

Safiuddin, M., West, J. S., & Soudki, K. a. (2011). Flowing ability of the mortars formulated from self-compacting concretes incorporating rice husk ash. *Construction and Building Materials*, *25*(2), 973–978. doi:10.1016/j.conbuildmat.2010.06.084

Sage, A.P. (1998), Risk management for sustainable development, Proceedings of the IEEE International Conference on System, Man and Cybernetics, Vol. 5, 1998, pp. 4815-4819.

Şahmaran, M., Christianto, H. A., & Yaman, İ. Ö. (2006). The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars. *Cement and Concrete Composites*, *28*(5), 432–440. doi:10.1016/j.cemconcomp.2005.12.003

Schuurmans A, Rouwette R, Vonk N, Broers J, Rijnsburger H and H. Pietersen, (2005): LCA of Finer Sand in Concrete. Int J LCA 10 (2) 131–135

Siddique, R. (2011). Properties of self-compacting concrete containing class F fly ash. *Materials & Design*, *32*(3), 1501–1507. doi:10.1016/j.matdes.2010.08.043

Siddique, R., & Rajor, A. (2012). Use of cement kiln dust in cement concrete and its leachate characteristics. *Resources, Conservation and Recycling*, *61*, 59–68. doi:10.1016/j.resconrec.2012.01.006

Sidney Mindess, J Francis Young & David Darwin, (2003). Concrete. Upper Saddle River, NJ. Prentice Hall 2nd Edition.

Struble, L., & Godfrey, J. (2004). How Sustainable Is Concrete? *International Workshop on Sustainable Development and Concrete Technology*, 201–211.

Soo, T.P. (2011). Presentation to NRMCA for Proposed Eco-labelled Concrete. Kuala Lumpur, Malaysia

Tam, V. W. Y. (2008). Economic comparison of concrete recycling: A case study approach. *Resources, Conservation and Recycling*, *52*(5), 821–828. doi:10.1016/j.resconrec.2007.12.001

Turk, K. (2012). Viscosity and hardened properties of self-compacting mortars with binary and ternary cementitious blends of fly ash and silica fume. *Construction and Building Materials*, *37*, 326–334. doi:10.1016/j.conbuildmat.2012.07.081

Uysal, M., & Sumer, M. (2011). Performance of self-compacting concrete containing different mineral admixtures. *Construction and Building Materials*, *25*(11), 4112–4120. doi:10.1016/j.conbuildmat.2011.04.032

Uysal, M., & Yilmaz, K. (2011). Effect of mineral admixtures on properties of self-compacting concrete. *Cement and Concrete Composites*, *33*(7), 771–776. doi:10.1016/j.cemconcomp.2011.04.005

Van den Heede, P., & De Belie, N. (2012). Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations. *Cement and Concrete Composites*, *34*(4), 431–442. doi:10.1016/j.cemconcomp.2012.01.004

Wiedman, T. and Minx, J. (2008). (2008). A Definition of “ Carbon Footprint .” In *Pertsova, Ecological Economics Research Trends* (Vol. 07–01, pp. 1–11). Hauppauge NY, USA.: Nova Science Publishers.

Wimpenny, D. (2009). Low Carbon Concrete – Options for the Next Generation of Infrastructure.

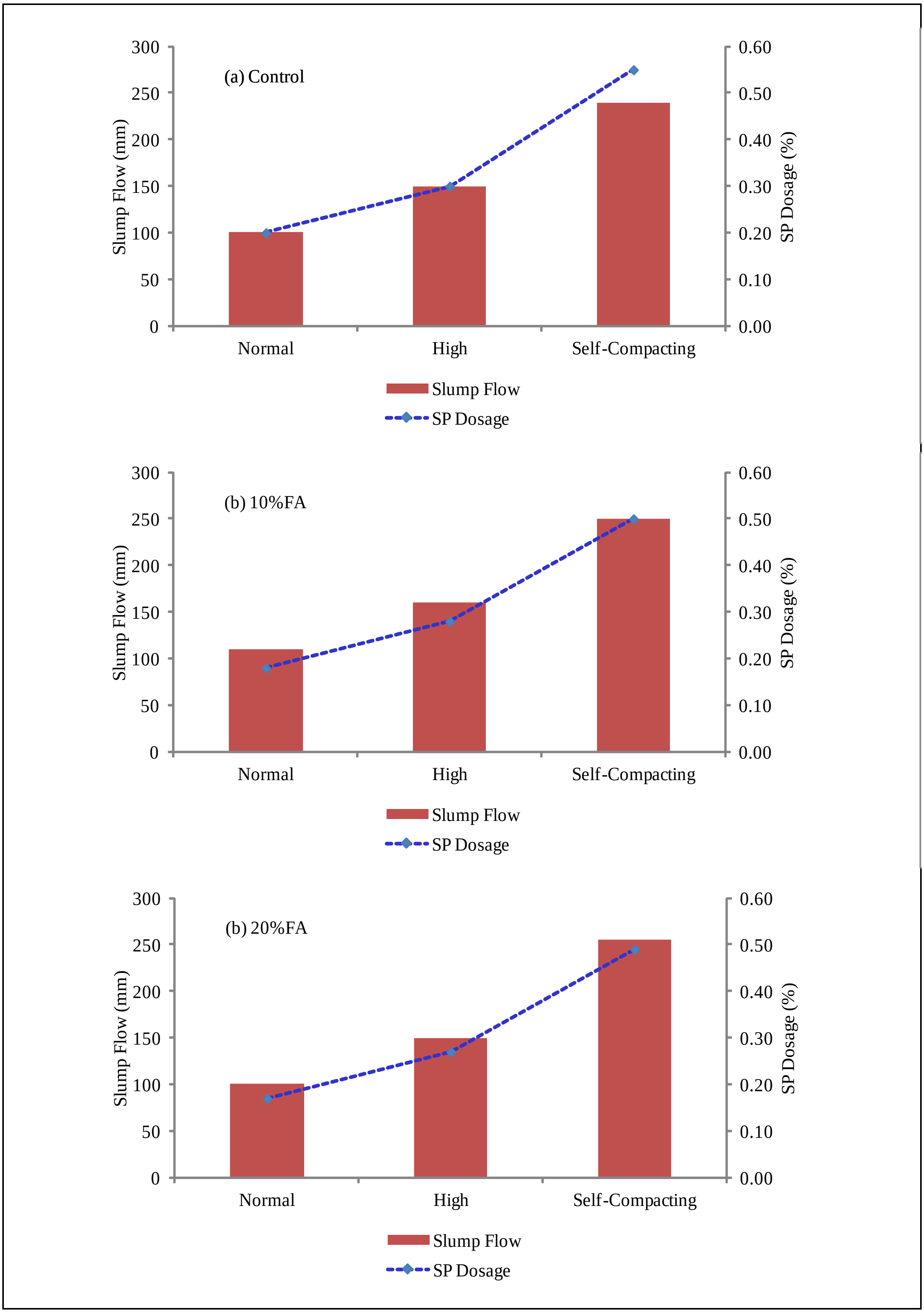
World Energy Council. Pursuing sustainability : 2010 assessment of country energy and climate policies. Available at : http://www.worldenergy.org/publications/2841.asp;2010 [accessed 12.05.2012]

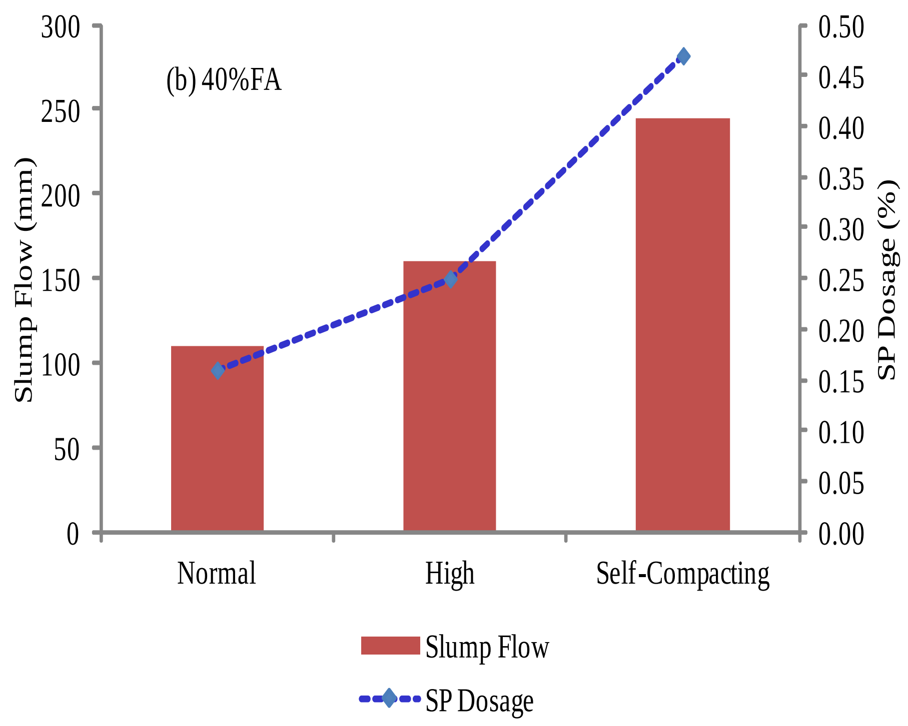
Yang, K.-H., Song, J.-K., & Song, K.-I. (2013). Assessment of CO2 reduction of alkali-activated concrete. *Journal of Cleaner Production*, *39*, 265–272. doi:10.1016/j.jclepro.2012.08.001

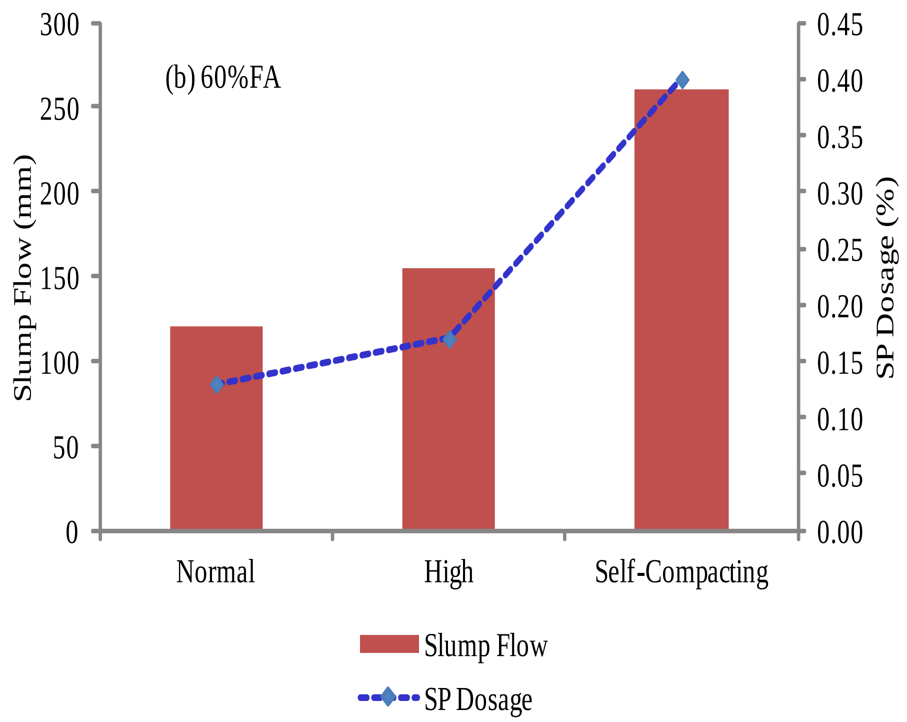
YTL Cement (2011). Report No. ETRC 257/16/990. Kuala Lumpur, Malaysia.

Zhang, T., Gao, P., Gao, P., Wei, J., & Yu, Q. (2013). Effectiveness of novel and traditional methods to incorporate industrial wastes in cementitious materials—An overview. *Resources, Conservation and Recycling*, *74*, 134–143. doi:10.1016/j.resconrec.2013.03.003

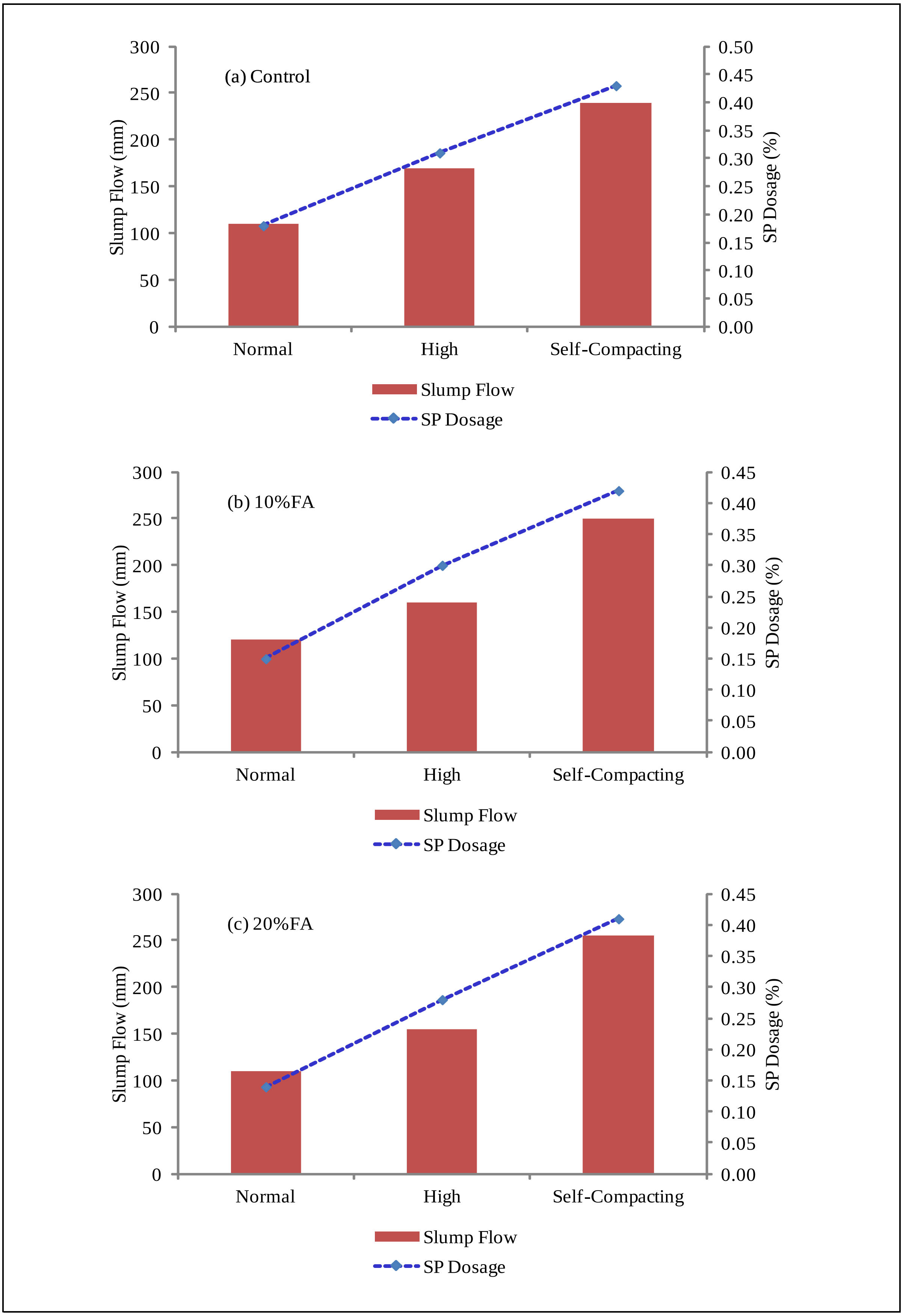
APPENDIX 1 – FIGURE FOR SLUMP FLOW AND SP DOSAGE W/B 0.40

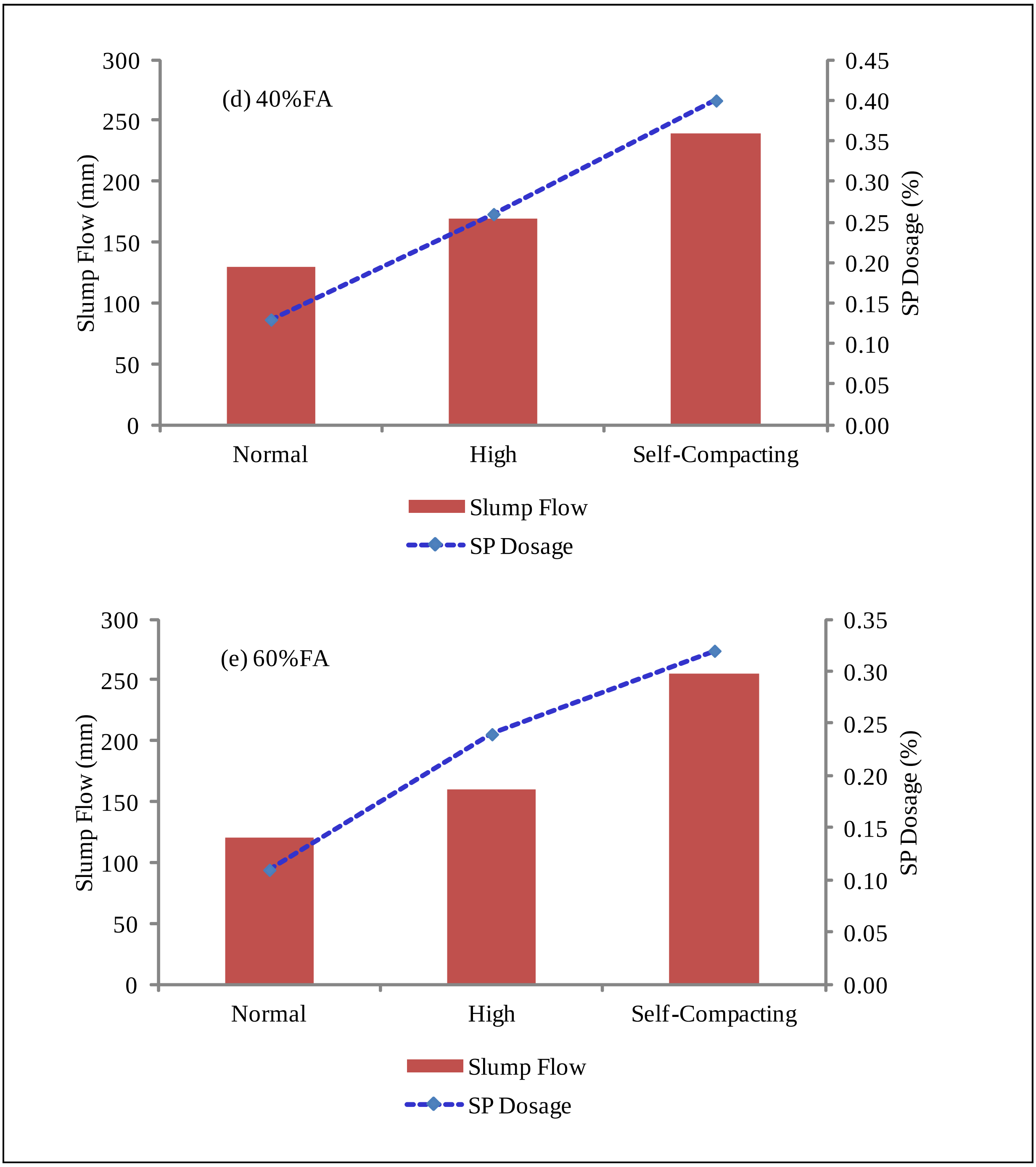



(b) 40%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage


(b) 60%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage

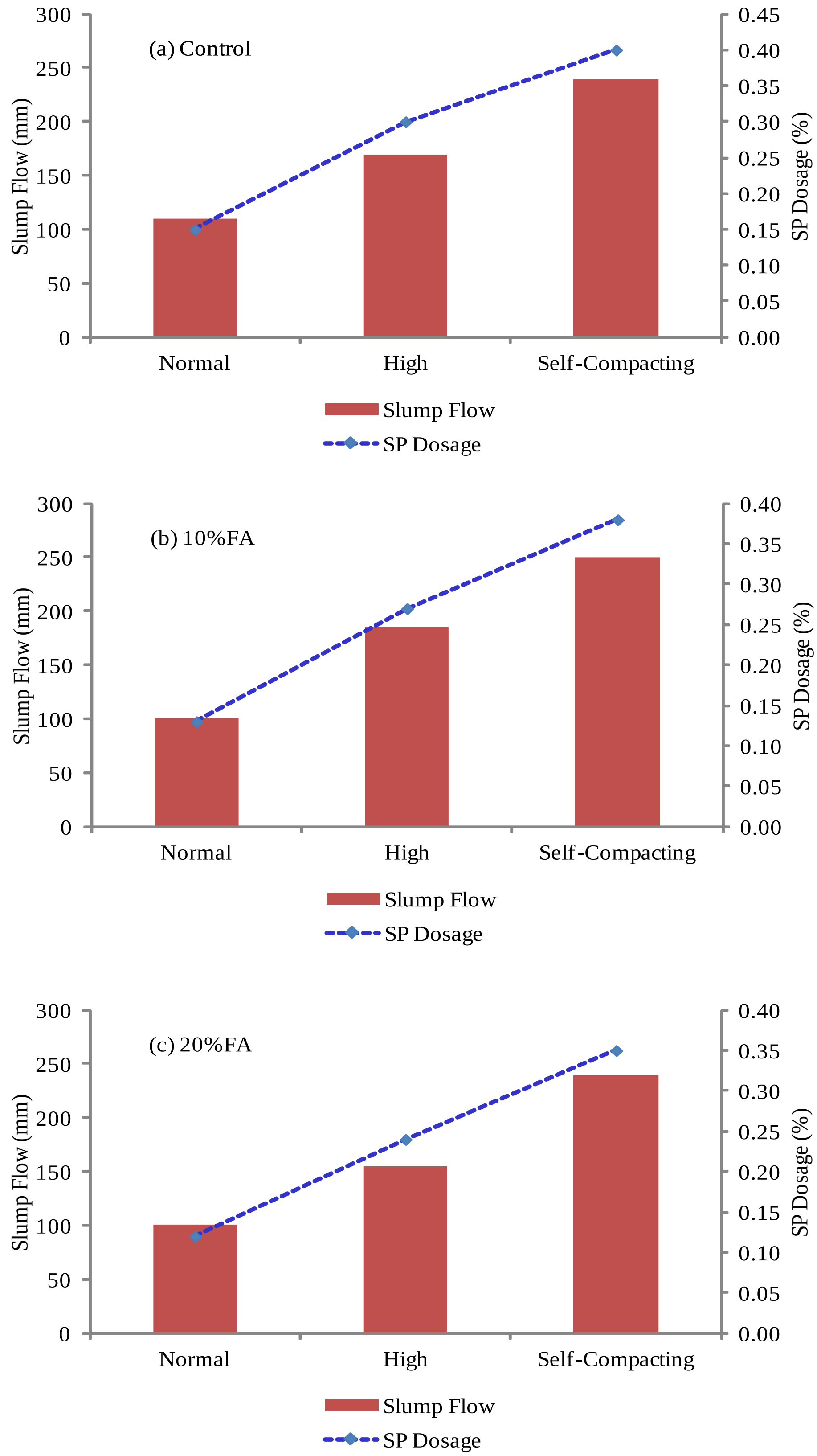
APPENDIX 2 – FIGURE FOR SLUMP FLOW AND SP DOSAGE W/B 0.45

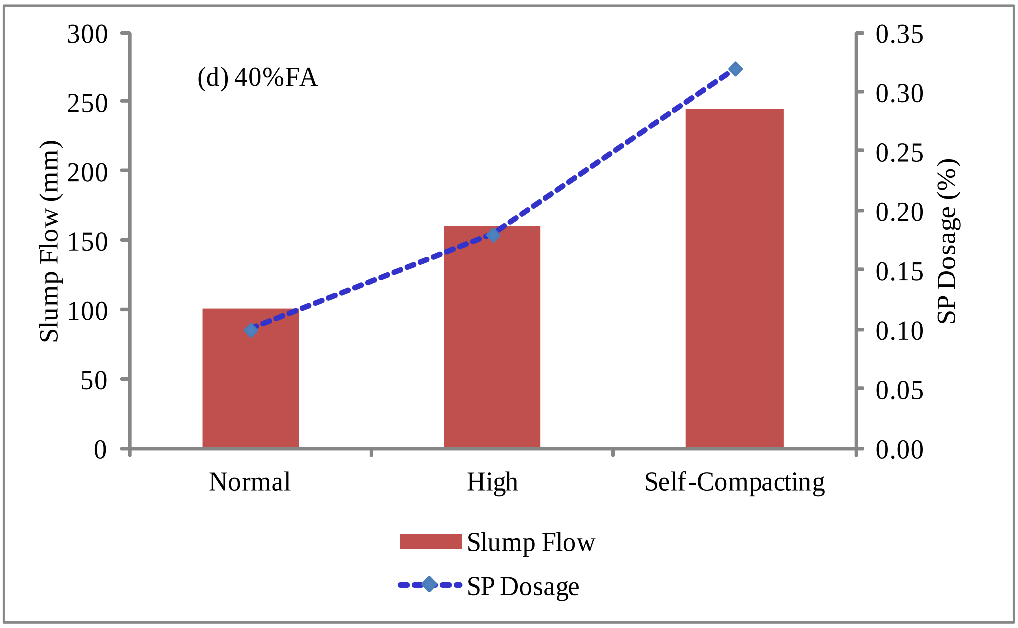


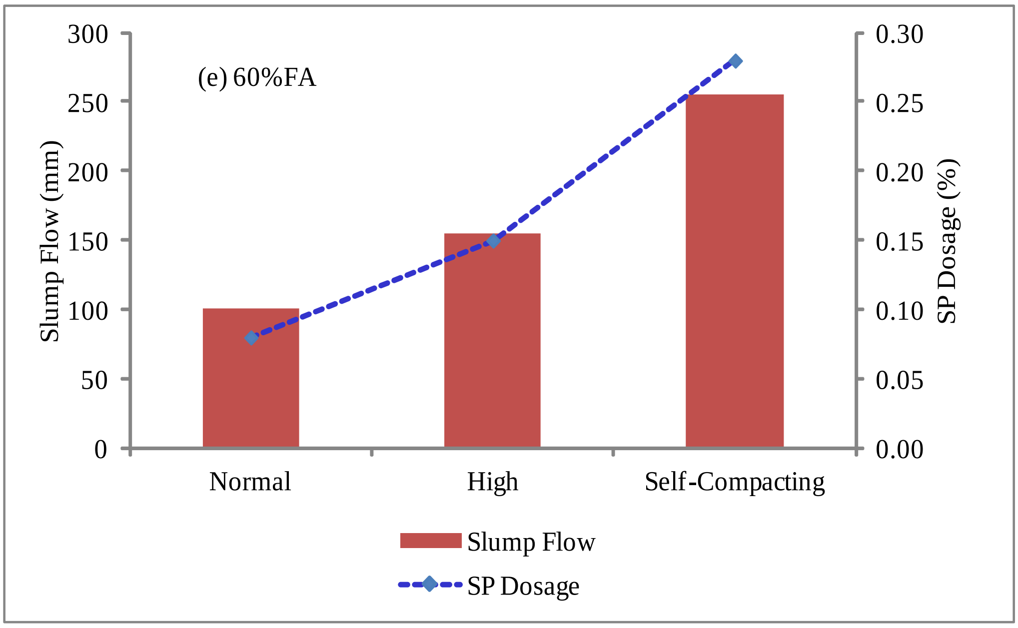


(d) 40%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage
(e) 60%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage

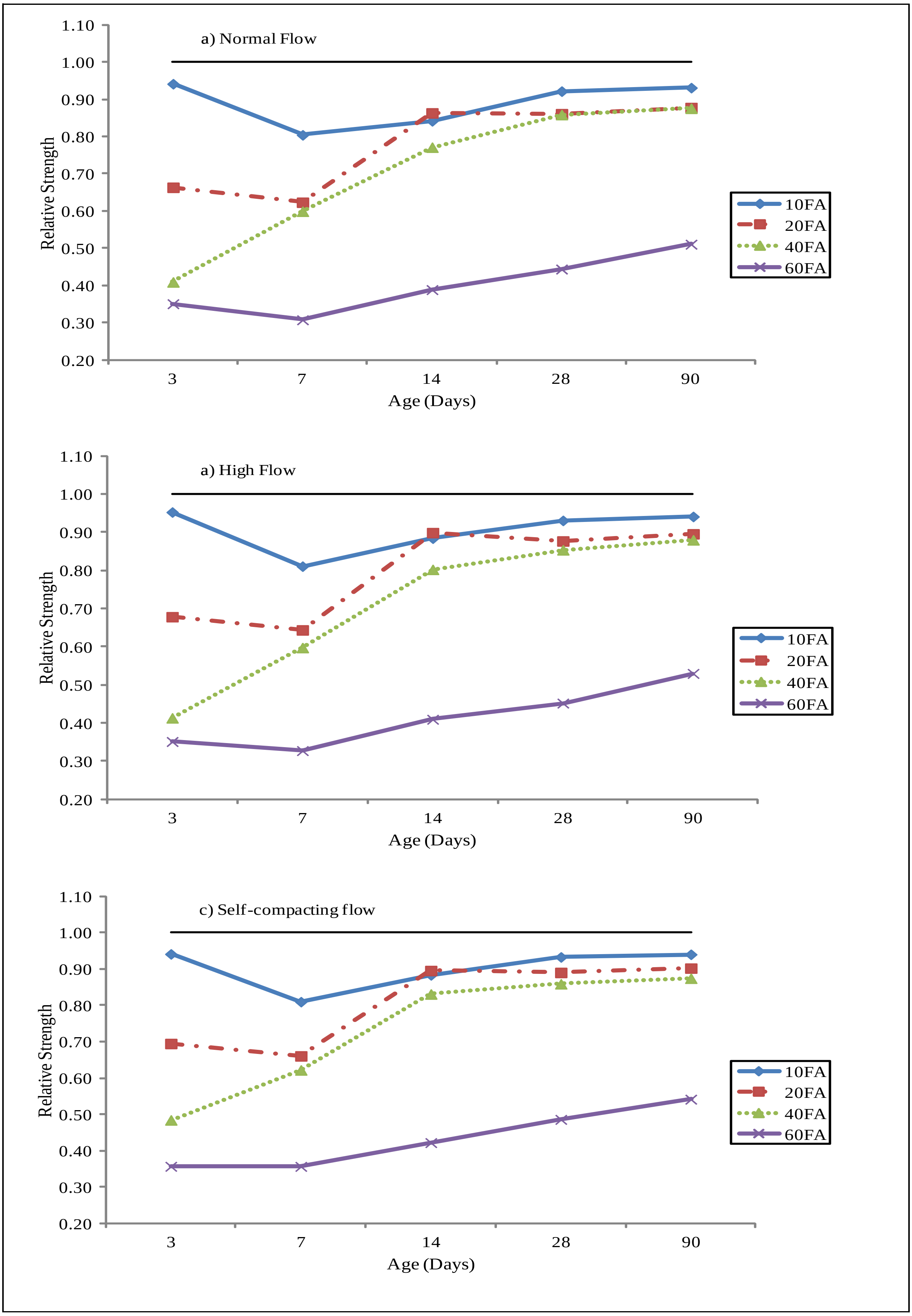
APPENDIX 3 – FIGURE FOR SLUMP FLOW AND SP DOSAGE W/B 0.50



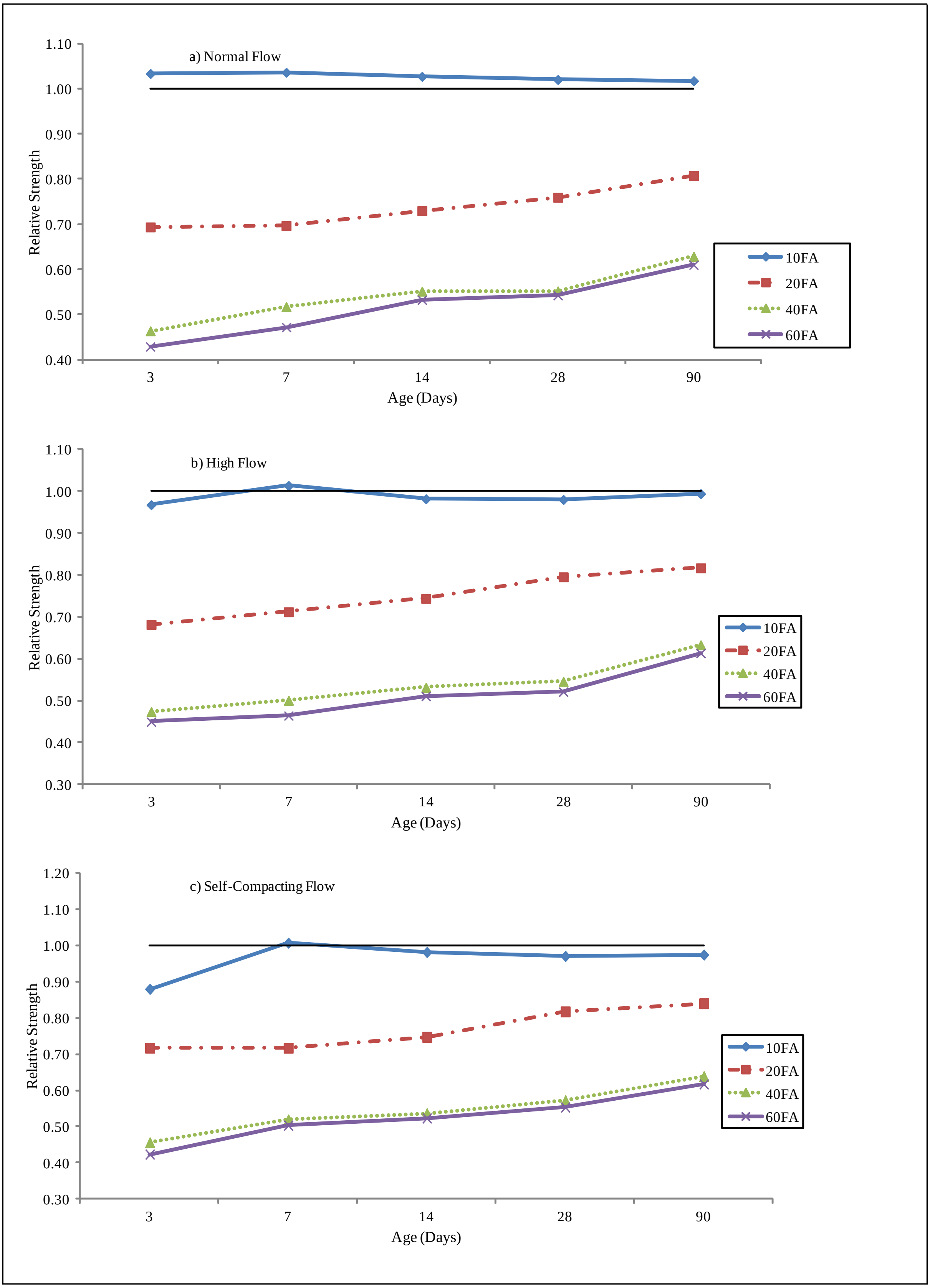

(d) 40%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage


(e) 60%FA
Slump Flow (mm)
SP Dosage (%)
300
250
200
150
100
50
0
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Normal
High
Self-Compacting
Slump Flow
SP Dosage

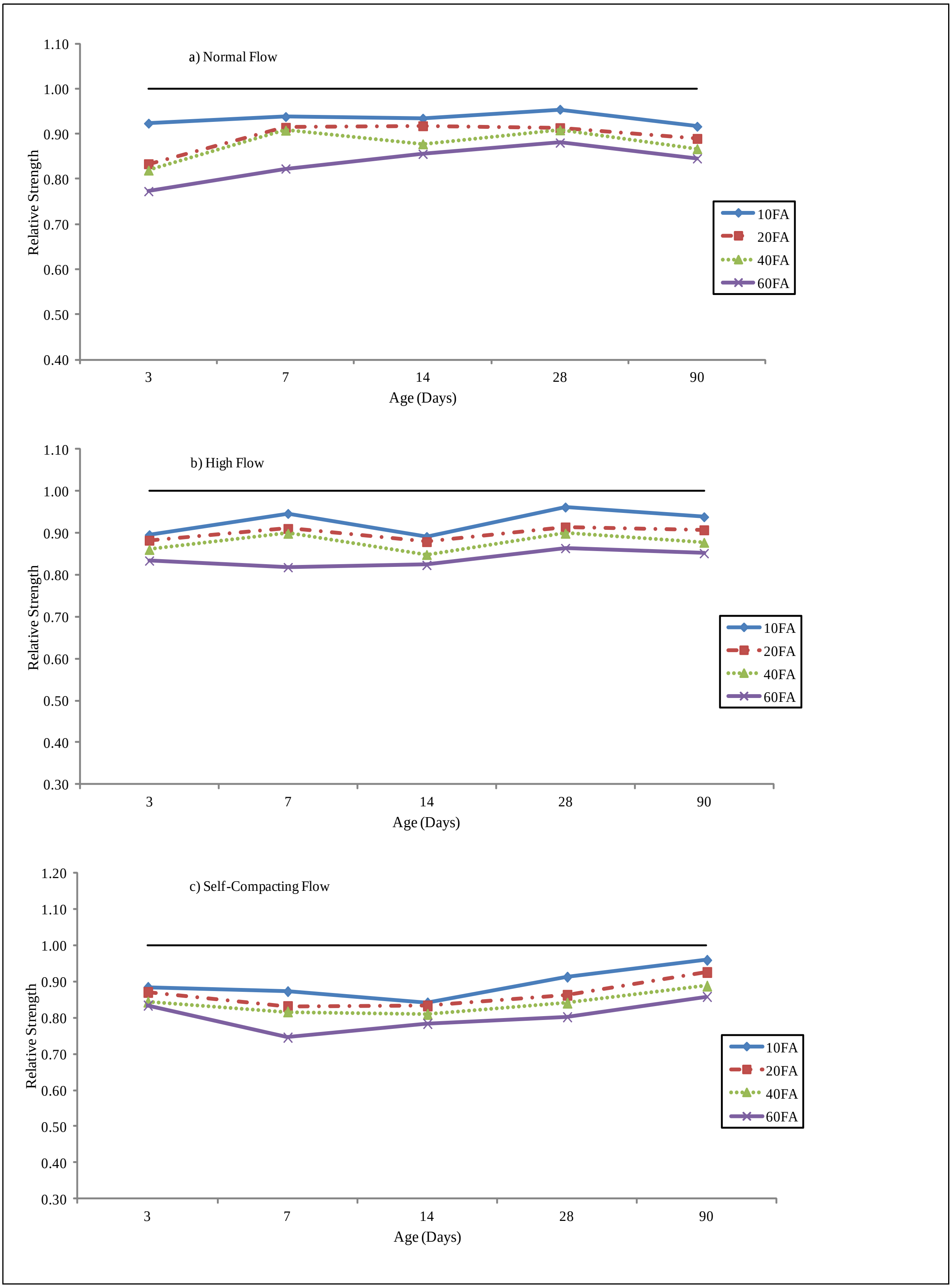
APPENDIX 4 – FIGURE FOR RELATIVE STRENGTH W/B 0.40



APPENDIX 5 – FIGURE FOR RELATIVE STRENGTH W/B 0.45



APPENDIX 6 – FIGURE FOR RELATIVE STRENGTH W/B 0.50



APPENDIX 7 – COMPRESSIVE STRENGTH W/B 0.35

Mixture	Compressive Strength (Mpa) *				
	3 days	**7 days**	**14 days**	**28 days**	**90 days**
C - 0.35 - N	32.89 *1.20*	44.25 *1.36*	55.70 *0.28*	62.95 *0.30*	65.74 *0.13*
C - 0.35 - H	58.39 *0.52*	62.76 *0.19*	70.05 *0.41*	74.61 *0.23*	84.38 *1.94*
C - 0.35 - SCM	59.06 *0.65*	67.81 *0.85*	74.71 *1.34*	78.77 *0.72*	88.62 *0.38*
10FA-0.35-N	39.41 *0.58*	58.20 *0.19*	65.37 *1.94*	70.13 *1.89*	73.05 *1.89*
10FA-0.35-H	45.16 *0.64*	59.03 *0.48*	67.71 *0.45*	77.88 *0.16*	82.10 *0.55*
10FA-0.35-SCM	54.54 *0.11*	69.33 *1.04*	80.58 *0.08*	87.63 *2.80*	91.92 *0.38*
20FA-0.35-N	35.13 *0.94*	41.96 *0.43*	55.45 *0.26*	60.29 *0.18*	73.04 *0.64*
20FA-0.35-H	39.40 *0.68*	53.45 *0.38*	63.49 *0.80*	72.60 *0.24*	87.56 *0.39*
20FA-0.35-SCM	40.10 *1.07*	54.44 *0.24*	65.16 *0.12*	75.67 *0.41*	90.40 *0.30*
40FA-0.35-N	17.11 *0.27*	32.66 *0.18*	39.52 *1.26*	53.70 *0.76*	72.69 *0.94*
40FA-0.35-H	22.99 *0.26*	36.11 *0.65*	46.48 *0.33*	58.23 *0.31*	77.47 *1.04*
40FA-0.35-SCM	25.66 *0.80*	41.17 *0.23*	52.47 *0.36*	62.31 *0.12*	82.27 *0.27*
60FA-0.35-N	17.99 *0.12*	28.05 *0.58*	33.41 *1.15*	42.51 *2.05*	58.70 *0.31*
60FA-0.35-H	19.01 *0.34*	29.09 *0.71*	38.31 *0.60*	47.26 *0.44*	61.70 *1.06*
60FA-0.35-SCM	22.20 *0.18*	32.28 *0.46*	40.83 *1.03*	50.63 *0.60*	63.62 *0.24*

* Standard deviation within ± 3% is indicated in italic

APPENDIX 8 – COMPRESSIVE STRENGTH W/B 0.40

Mixture	Compressive Strength (Mpa) *				
	3 days	**7 days**	**14 days**	**28 days**	**90 days**
C - 0.40 - N	44.63 *1.59*	59.94 *1.79*	62.87 *1.91*	66.45 *0.39*	75.50 *0.87*
C - 0.40 - H	47.84 *0.29*	62.19 *0.13*	65.23 *0.10*	71.69 *0.62*	78.66 *0.21*
C - 0.40 - SCM	50.82 *1.26*	64.66 *1.58*	67.08 *0.77*	73.80 *2.72*	82.73 *1.87*
10FA-0.40-N	42.02 *0.53*	48.21 *0.70*	52.93 *0.40*	61.24 *1.79*	70.29 *0.94*
10FA-0.40-H	45.58 *0.41*	50.43 *0.51*	57.67 *2.10*	66.72 *2.72*	74.03 *0.26*
10FA-0.40-SCM	47.83 *0.39*	52.36 *0.34*	59.26 *1.41*	68.84 *0.14*	77.77 *1.21*
20FA-0.40-N	29.61 *1.07*	37.37 *1.05*	54.27 *0.80*	57.22 *1.91*	66.27 *0.45*
20FA-0.40-H	32.46 *0.13*	40.04 *2.18*	58.63 *1.46*	62.86 *0.81*	70.45 *0.91*
20FA-0.40-SCM	35.30 *0.85*	42.71 *0.45*	60.06 *0.75*	65.69 *0.20*	74.62 *1.18*
40FA-0.40-N	18.27 *0.60*	35.92 *0.58*	48.48 *1.75*	57.05 *0.11*	66.10 *0.43*
40FA-0.40-H	19.78 *0.38*	37.16 *1.14*	52.34 *0.71*	61.19 *1.31*	69.21 *0.69*
40FA-0.40-SCM	24.62 *0.61*	40.21 *0.72*	55.73 *1.12*	63.38 *1.34*	72.31 *1.07*
60FA-0.40-N	15.67 *0.44*	18.46 *0.94*	24.46 *1.17*	29.52 *2.05*	38.57 *0.96*
60FA-0.40-H	16.82 *0.77*	20.38 *0.41*	26.74 *1.18*	32.42 *0.93*	41.69 *1.08*
60FA-0.40-SCM	18.14 *1.24*	23.07 *1.79*	28.32 *0.62*	35.87 *1.41*	44.80 *0.95*

* Standard deviation within ± 3% is indicated in italic

APPENDIX 9 – COMPRESSIVE STRENGTH W/B 0.45

Mixture	Compressive Strength (Mpa) *				
	3 days	**7 days**	**14 days**	**28 days**	**90 days**
C - 0.45 - N	30.74 *0.77*	41.93 *0.67*	49.17 *1.40*	56.93 *0.81*	65.98 *0.92*
C - 0.45 - H	34.79 *0.63*	45.82 *0.89*	54.43 *0.17*	61.72 *1.67*	69.73 *0.42*
C - 0.45 - SCM	40.76 *0.68*	48.95 *0.16*	57.28 *0.81*	64.43 *1.85*	73.48 *1.17*
10FA-0.45-N	31.77 *2.41*	43.44 *0.81*	50.50 *0.40*	58.08 *1.15*	67.13 *0.94*
10FA-0.45-H	33.68 *0.25*	46.45 *1.27*	53.45 *0.20*	60.51 *1.54*	69.33 *1.27*
10FA-0.45-SCM	35.83 *0.95*	49.26 *0.39*	56.17 *0.85*	62.48 *0.67*	71.53 *1.31*
20FA-0.45-N	21.33 *0.16*	29.21 *0.55*	35.88 *0.69*	43.24 *0.10*	53.29 *1.14*
20FA-0.45-H	23.73 *0.47*	32.64 *1.40*	40.51 *0.32*	49.11 *1.37*	56.98 *0.87*
20FA-0.45-SCM	29.21 *0.75*	35.07 *0.29*	42.77 *1.83*	52.62 *0.58*	61.67 *1.24*
40FA-0.45-N	14.25 *0.26*	21.68 *0.34*	27.11 *0.32*	31.42 1.16	41.47 *0.83*
40FA-0.45-H	16.50 *0.50*	22.96 *0.31*	28.96 *2.01*	33.71 *0.77*	44.18 *1.23*
40FA-0.45-SCM	18.56 *0.23*	25.39 *1.25*	30.69 *0.37*	36.83 *1.43*	46.88 *0.87*
60FA-0.45-N	13.18 *1.15*	19.78 *0.93*	26.17 *0.82*	30.87 *1.34*	40.24 *0.52*
60FA-0.45-H	15.65 *0.78*	21.29 *0.64*	27.82 *1.04*	32.19 *0.90*	42.78 *0.89*
60FA-0.45-SCM	17.24 *1.39*	24.61 *0.75*	29.94 *0.44*	35.61 *0.32*	45.31 *0.59*

* Standard deviation within ± 3% is indicated in italic

APPENDIX 10 – COMPRESSIVE STRENGTH W/B 0.50

Mixture	Compressive Strength (Mpa) *				
	3 days	**7 days**	**14 days**	**28 days**	**90 days**
C - 0.50 - N	18.27 *0.73*	25.18 *0.25*	30.47 *1.33*	38.47 *0.14*	51.02 *1.07*
C - 0.50 - H	20.41 *0.58*	28.23 *0.92*	35.73 *0.29*	42.87 *1.41*	54.63 *1.12*
C - 0.50 - SCM	23.92 *0.29*	34.21 *0.72*	41.90 *1.41*	50.19 *0.09*	58.24 *1.05*
10FA-0.50-N	16.87 *0.61*	23.62 *0.39*	28.47 *1.33*	36.71 *0.77*	46.76 *1.07*
10FA-0.50-H	18.29 *0.68*	26.73 *0.54*	31.86 *0.93*	41.25 *1.03*	51.30 *1.57*
10FA-0.50-SCM	21.14 *0.09*	29.84 *0.16*	35.24 *0.19*	45.78 *0.15*	55.83 *1.14*
20FA-0.50-N	15.23 *0.67*	23.02 *0.13*	27.96 *0.75*	35.14 *1.12*	45.39 *1.09*
20FA-0.50-H	18.02 *0.32*	25.72 *0.65*	31.43 *0.42*	39.21 *0.67*	49.59 *0.35*
20FA-0.50-SCM	20.81 *0.89*	28.42 *0.43*	34.89 *1.98*	43.27 *0.86*	53.87 *0.64*
40FA-0.50-N	14.97 *0.22*	22.86 *0.56*	26.74 *0.21*	34.95 *0.45*	44.23 *1.69*
40FA-0.50-H	17.57 *0.98*	25.39 *1.78*	30.33 *0.67*	38.57 *1.02*	47.96 *0.93*
40FA-0.50-SCM	20.17 *0.34*	27.92 *1.67*	33.91 *0.39*	42.18 *0.82*	51.68 *0.74*
60FA-0.50-N	14.12 *0.92*	20.72 *0.41*	26.07 *1.21*	33.87 *1.08*	43.14 *0.71*
60FA-0.50-H	17.03 *0.86*	23.11 *0.79*	29.44 *0.29*	37.05 *0.69*	46.55 *1.49*
60FA-0.50-SCM	19.94 *0.26*	25.49 *0.64*	32.81 *0.94*	40.23 *1.09*	49.95 *0.78*

* Standard deviation within ± 3% is indicated in italic